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**E:F**

STUDY OF SYSTEMS AND TECHNOLOGY FOR LIQUID HYDROGEN  
PRODUCTION INDEPENDENT OF FOSSIL FUELS

FINAL REPORT

TO:

John F. Kennedy Space Center, NASA  
Procurement Office  
Kennedy Space Center, FL 32899

BY:

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Charles R. Baker

UNDER CONTRACT NO. NAS10-10541

August 1983

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## ABSTRACT

This report, in support of NASA-Kennedy Space Center (KSC) planning for future expanded supplies of liquid hydrogen fuel for space vehicle logistic support, addresses the potential use of non-fossil energy resources and conversion technologies. This approach contrasts with today's natural gas-based liquid hydrogen supply and with other fossil-based alternatives (e.g., coal-gasification).

Based on KSC siting and logistics requirements, and the non-fossil energy resources available at the Center, a large number of applicable energy technologies and system candidates are identified and characterized. A two-stage screening of these in light of specific criteria was then accomplished, resulting in the identification of two leading candidates as non-fossil system approaches. Conceptual-level design and costing of these revealed their technical feasibility as sited at KSC, and the potential for product cost-competitiveness with conventional supply approaches in the 1990-2010 time period.

These findings led to the documentation of a set of key observations, conclusions, and recommendations. Several supporting technical appendices are included.

### Key Words

Liquid Hydrogen, Non-Fossil Energy Technology and Systems, Solar Energy Conversion, Water Electrolysis, Cryogenic Liquefaction, Space Vehicle Propellants Supply.

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## SUMMARY

Currently, liquid hydrogen fuel for space vehicles such as the Space Shuttle is produced through the natural gas steam-reforming process, followed by an energy-intensive liquefaction process. With considerable uncertainty as to future availability and costs of electricity and natural gas--and fossil feedstocks generally--the option of basing liquid hydrogen production on non-fossil energy resources (solar, nuclear, geothermal) is of interest to NASA planners. Accordingly, NASA's John F. Kennedy Space Center (KSC) sponsored this initial assessment, "Study of Systems and Technology for Liquid Hydrogen Production Independent of Fossil Fuels," as carried out by the present industrial contractor team.

Following a general background discussion in which KSC's specific requirements and certain coproduct options (e.g., coproduced oxygen, heat) are quantified, candidate non-fossil primary energy-based technologies and systems are introduced and reviewed. Along with this, the non-fossil energy resources available to KSC--emphasis on actual Center sites--is surveyed and documented. Land availability and potential environmental impacts are also discussed.

A two-stage screening of candidate non-fossil-based technologies and systems was then carried out using sets of criteria developed for the study. These two stages involved (1) judgment of "technology readiness," in perspective with the state-of-the-art and KSC's time-of-deployment interest "window" of 1987-1992, up to the year 2000, and (2) relative economic performance of overall liquid hydrogen production systems based on applicable ones of these technologies. These screening results, as well as the prior work, were reviewed at KSC in the Study's interim briefing.

To provide a more-detailed illustration of leading candidate non-fossil liquid hydrogen production systems, two different systems were selected for conceptual design and more-detailed costing. These were solar-operated, stand-alone KSC-sited systems: one, photovoltaics (PV)-based, and the other involving the "power tower" (PT) approach, both of which are in the early-commercialization stage. Conventional water electrolysis and hydrogen liquefaction subsystems were integrated with the solar subsystem.

Concurrently, with numerous remaining technology/system candidates at hand (i.e., those screened), characteristically applicable in a later time-frame, a "technology tracking" methodology was documented to assist KSC in continuously evaluating essentially all the non-fossil future options available as perceived today.

The report closes with a summary of key observations, conclusions, and recommendations. The essence is that leading non-fossil liquid hydrogen production systems, given that (1) "optimistic but realizable" capital costs can be assumed, and (2) energy-intensive fossil-based supplies as nominally escalated over inflation, can, in fact, be competitive with current methods of supply in the 1990-2010 time period.

## 1. INTRODUCTION AND BACKGROUND

### Introduction

#### Contractor Study Team

Under NASA-Kennedy Space Center Contract No. NAS10-10541, E:F Technology, Inc. (E:F), carried out a "Study of Systems and Technology for Hydrogen Production Independent of Fossil Fuels" during the period September 1982 through May 1983. Assisting E:F, under consulting subcontracts, were:

- Mueller Associates, Inc. (MAI) - an architectural and engineering consultant firm with special capabilities in solar energy systems
- Linde Division, Union Carbide Corporation (Linde/UCC) - a leading industrial gas firm commercially involved in liquid hydrogen and oxygen production and delivery, and in numerous related technologies.

In addition, the following expert advisers were retained in the E:F study team (with area of expertise as indicated) on both a paid and unpaid basis:

- Dr. John A. Barclay, Los Alamos National Laboratory (LANL): magneto-caloric refrigeration-based hydrogen liquefiers (paid basis)
- Dr. Ja H. Lee, Vanderbilt University (located at NASA-Langley Research Center (NASA-LaRC)): low-temperature magnetohydrodynamic processes (paid basis)
- Mr. Omar Hancock, Florida Solar Energy Center (FSEC): local KSC insolation data and solar energy systems operational information (unpaid basis)
- Dr. Arden B. Walters, Florida Power & Light Company (FPL): electric utility perspective and technoeconomic information relating to potential grid-interfacing (unpaid basis).

The NASA technical study manager was Mr. Wally H. Boggs, NASA-KSC (DD FED) and the contracting officer was Ms. Ruth S. Walker, NASA-KSC (SI PRO-33).

#### Study Objectives and Methodology

This assessment was to examine all non-fossil-based liquid hydrogen production system schemes potentially capable of meeting KSC's demands beginning in the 1987-1992 time-frame. Following a preliminary characterization of such schemes, based on appropriate screening criteria, two sequential selections were made narrowing down the choices to two. However, the non-selected alternatives were to be briefly documented as well. Conceptual designs were to be documented for two "optimal" cost" non-fossil liquid hydrogen production systems, i.e., the two candidates selected in the screening process, above.

Specific technology program planning information was to be developed as appropriate for the two selected candidates and, to a lesser extent, for the full range of system possibilities. In this, appropriate quantitative and

qualitative criteria were to be suggested for periodic monitoring and evaluation of technological progress in the ongoing non-fossil energy research and development process. The purpose here is to assist in the planning/decision-making process relating to liquid hydrogen source-selection, facilities acquisition, etc., in the years ahead. In review, the principal objective of the study was to provide KSC planners and decision-makers with well-documented, authoritative information, guidelines, quantitative criteria, and appropriate contacts to:

1. Maximize KSC's understanding of Non-Fossil Derived Liquid Hydrogen (NFDLH<sub>2</sub>) production schemes, generally, and the more attractive nearer-term schemes, specifically.
2. Permit KSC "tracking" of NFDLH<sub>2</sub>-related technology/system development such that point-in-time competitiveness (with fossil-hydrogen production means) can be noted as early as possible.
3. Provide early planning input for the facility budgeting process anticipating the eventual acquisition of NFDLH<sub>2</sub>-production facilities at/associated with KSC.
4. Assist KSC in interpreting the planning and decision-making significance of both technical (e.g., new processes) and cost-related changes affecting both NFDLH<sub>2</sub>- and fossil-related hydrogen production schemes.

#### Background

This section of the report reviews the need for liquid hydrogen at KSC, the present means of acquiring this fuel by KSC in projected future increased quantities, the fossil- and non-fossil-based production alternatives, and how the specific study findings might assist KSC planning and decision-making in this respect.

#### Liquid Hydrogen Procurement and Use by KSC

Liquid hydrogen (with liquid oxygen) has become the staple fuel for space launch vehicles because of the superior specific impulse\* it provides in rocket engines. KSC was the first launch operations center to acquire and service liquid hydrogen for NASA's premier hydrogen-using space vehicle, the Atlas-Centaur in the mid-1960's. (The Centaur upper stage was the World's first liquid hydrogen-fueled space vehicle.) Used in the S-II and S-IVB (second and third) stages of the Saturn 5 and the S-IV and S-IVB (second) stage of the Saturn 1 and 1B Apollo earth-orbital mission vehicles, respectively, liquid hydrogen use expanded substantially at KSC through the late-1960's and early-1970's.

Now, with the completion of the R&D launches of the Space Shuttle-based STS (Space Transportation System), a rapidly increasing demand for liquid hydrogen is foreseen by KSC logistics planners. Figure 1-1, provided by KSC authorities responsible for propellant procurement and logistics operations, shows the liquid hydrogen demand expectation based on the order of 45 Space Shuttle launches annually by the late-1980's. This curve shows a peak usage of 13,000,000 lb/year, or about 22 million gallons/year. For perspective, Table 1-1 presents KSC's liquid hydrogen current requirements and costs, along with other propellants and expendables.

\* Isp - a direct measure of engine output thrust to input mass-flow of propellants (lb force per lb mass/second; or seconds).



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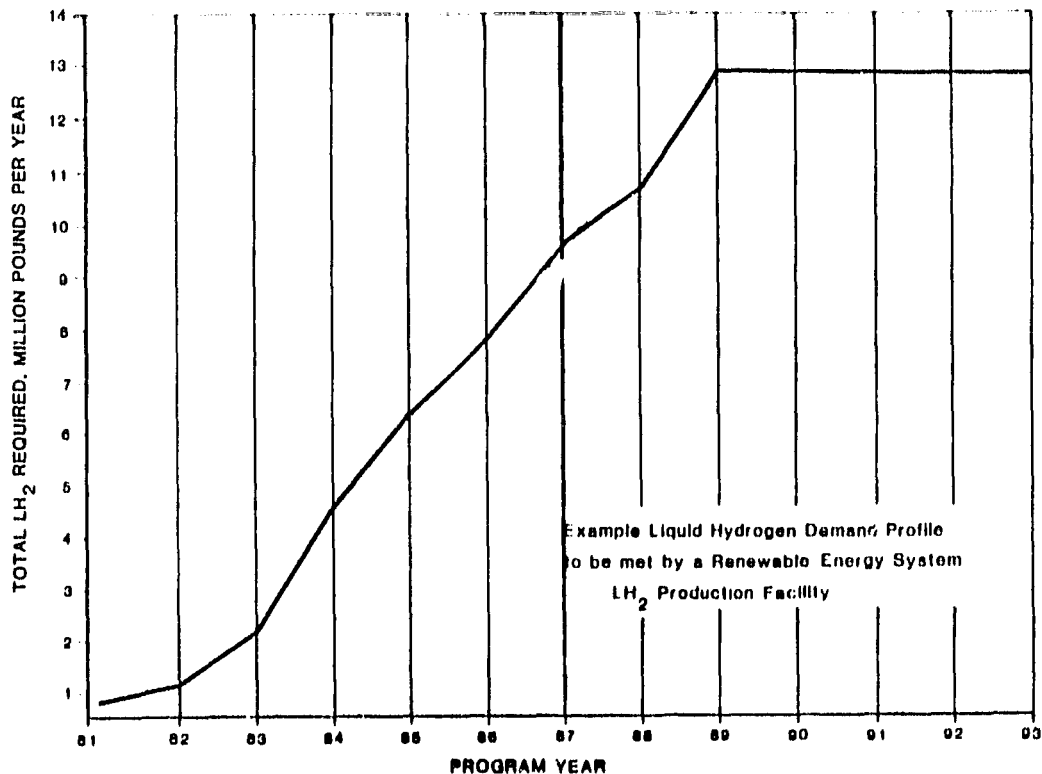


Figure 1-1. ANTICIPATED KSC LIQUID HYDROGEN REQUIREMENTS

Table 1-1. KSC CURRENT PROPELLANTS REQUIREMENTS COST  
PROPELLANTS MODEL FLIGHT SUPPORT<sup>2</sup>

PRODUCT/UNIT	FY-82 COSTS	ANNUAL BASE SUPPORT <sup>1</sup> QUANTITY/\$(000)		LAUNCH DEPENDENT QUANTITY/\$(000)		ONBOARD QUANTITY/\$(000)	
LH <sub>2</sub> /lb	\$ 1.23	84,000	\$ 103	88,800	\$109	227,800	\$280
GHe/mscf	53.00	10,080	534	1,070	57	30.3	2
LO <sub>2</sub> (A)/ton	85.41	2,100	179	492	42	672	57
MH/1b	6.77	--	--	--	--	13,000	88
N <sub>2</sub> O <sub>4</sub> /1b	.43	--	--	--	--	20,500	9
N <sub>2</sub> H <sub>4</sub> /1b	7.18	--	--	367	3	963	7
LN <sub>2</sub> /ton	93.37	360	34	8	1	--	--
GN <sub>2</sub> /mscf	7.18	360,000	2,585	40,000	287	3.5	--
LO <sub>2</sub> (F)/ton	283.00	--	--	28.5	8	1.5	1
Solvent 113/1b	.56	615,000	344	--	--	--	--
OTHER	--	--	189	--	25	--	22
TOTAL		\$3,968		\$532		\$466	

ANNUAL BASE SUPPORT  
QUANTITY/\$(000)  
TWO PADS OPERATIONAL

GHe	13,440	\$ 712
GN <sub>2</sub>	540,000	3,877
LO <sub>2</sub> (A)	3,520	301
LH <sub>2</sub>	168,000	207

<sup>1</sup>One Pad Operational  
<sup>2</sup>No Payloads

## Liquid Hydrogen Production Means--Today and Tomorrow

KSC presently procures its liquid hydrogen under contract to Air Products & Chemicals, Inc., with deliveries from the company's New Orleans, LA, plant by over-the-road trucking (via standing 13,000 gallon trailers).<sup>\*</sup> This hydrogen, like the bulk of industrial gas hydrogen in the U.S. today, is produced through the well-developed steam-reforming of natural gas process.

Currently, in the U.S., natural gas-produced liquid hydrogen is the lowest cost option for users purchasing merchant hydrogen, i.e., industrial-gas product. However, future natural gas supplies and costs are uncertain in a "decades-ahead" purview. Further, with current price deregulation trends, natural gas costs are expected to increase sharply in the years just ahead. Hydrogen can be produced from water and essentially any fossil resource, including naphtha, heavier oils (including resid), and coal, etc. However, particularly in view of costs and competing demands and importation problems with regard to oil (e.g., transportation, home-heating), petroleum is not viewed as a likely source of future industrial-gas hydrogen.

For the U.S., with its large domestic supplies, a current perception is that coal appears to be the principal fossil-energy candidate for future U.S. production of hydrogen. The original present-study solicitation observed: "Coal, therefore, should be considered as a potential feedstock, as an interim scheme, until a fully-renewable scheme is available" (Reference 1-1). KSC is, in fact, proceeding separately (in parallel with the present non-fossil-based assessment) to assess the potential of coal-derived liquid hydrogen in the context of a "polygeneration" facility (Reference 1-2).

### Comparative Costs of Fossil-Produced Hydrogen

Since the development of alternative fossil- and non-fossil- (e.g., renewable) based hydrogen production schemes will depend heavily on comparative costs of the hydrogen produced, it is of interest to examine associated cost projections. Figure 1-2 presents one set of such projections through 1990. These estimates were provided by Kinetic Technology International (KTI Corporation), Pasadena, CA. (KTI is a principal supplier of industrial steam-reforming facilities.) Current 1982 costs and earlier 1974 (reference) costs are shown. Note that these costs are strictly on an inter-fossil resource comparison basis (no absolute costs are projected).

The dashed-in higher costs labeled "ARC 1990-2000 Projections" refer to projected higher fossil resource cost projections by DOE in its 1981 ARC mid-price scenario. These higher cost possibilities are of interest from the point of view that non-fossil schemes--typically higher in cost--may be able to compete earlier if such higher fossil-derived hydrogen costs actually come to pass.

---

<sup>\*</sup> In the interest of expanding their liquid hydrogen transport options, KSC recently acquired (from another NASA facility) four 34,000 gallon capacity liquid hydrogen rail tank cars. Following refurbishment and certification of the cars, over-rail trial runs are presently underway from New Orleans to KSC.

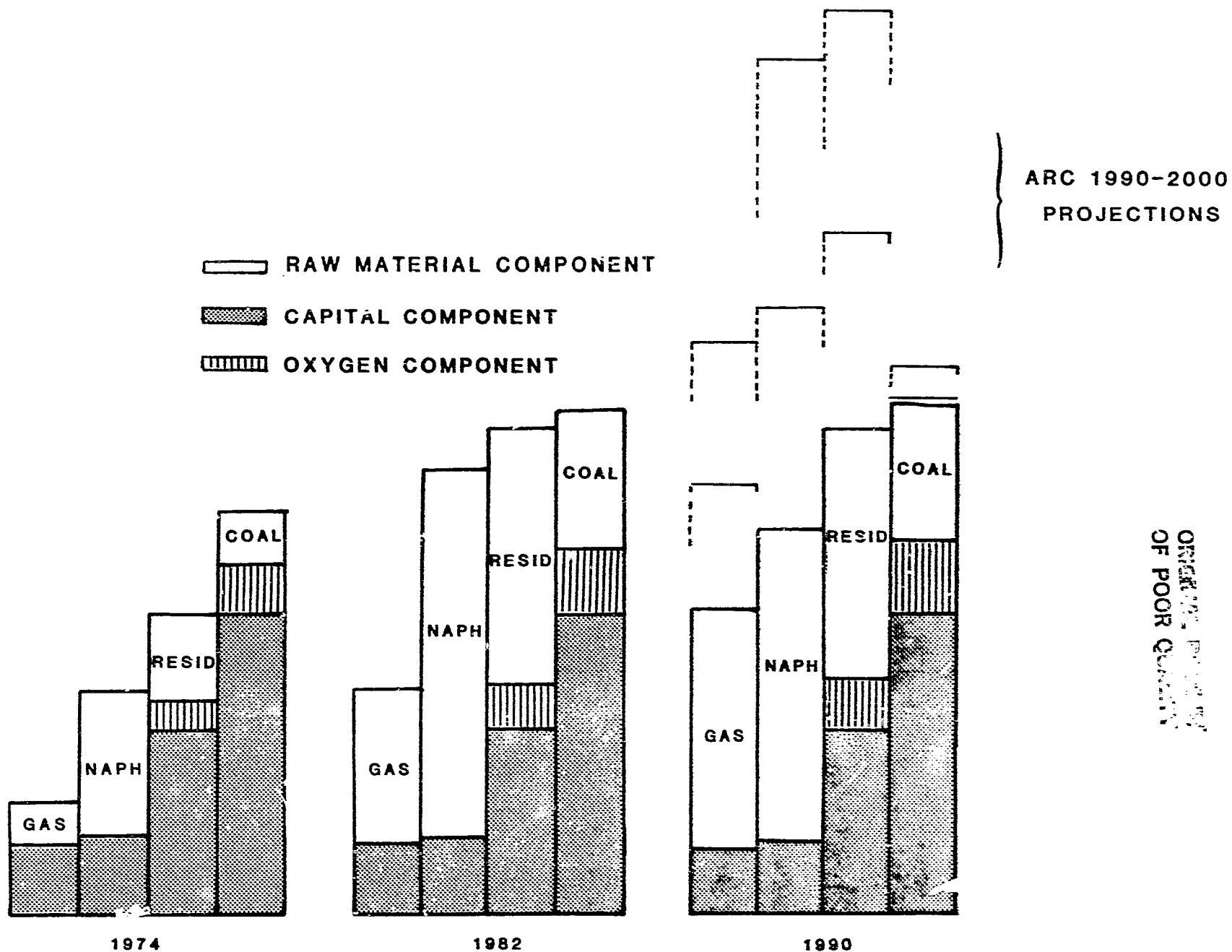


Figure 1-2. THE RELATIVE COST OF PRODUCING HYDROGEN FROM FOSSIL FUELS, 1974-1986, CONSTANT \$ 1982 BASIS (Source: KTI/CPA Estimates.)

## The Alternative of NFDLH<sub>2</sub> for KSC

In view of the long-term uncertainties associated with natural gas produced hydrogen, and with fossil-derived hydrogen generally (including coal gasification), KSC planners wish, out of prudence, to assess the non-fossil-derived (NFD) hydrogen alternatives. The present study represents an initial step in this direction. Specifically, as stated in the KSC original study solicitation (Reference 1-1):

"This study shall survey methods and select viable candidates for providing liquid hydrogen for U.S. space launch use independent of fossil fuels starting in 1987 or 1992, or whenever the particular technologies and economic trade-offs appear favorable. The candidates shall be examined in larger system context where strong interaction with other resources exists (i.e., energy coproduction) and where environmental interactions are significant. (emphasis added)

### Non-Fossil Energy Conversion as Applicable to Hydrogen Production

Candidate NFDLH<sub>2</sub> production possibilities are the subject of Section 3 of this document. In terms of the basic energy resource, the alternatives fit into four categories:

- Nuclear - fission and fusion processes
- Solar - direct and indirect (e.g., wind, hydropower) processes
- Geothermal - natural (e.g., geysers) and technologically-accessed (e.g., dry/hot-rock) processes
- Gravitational - principally, tidal energy (also ties in with certain solar-indirect processes such as hydropower).

### Water-Splitting Processes as Applicable to Hydrogen Production

To these various energy-conversion processes must be integrated a water-splitting process since water is the prospective non-fossil "feedstock" from which its elemental constituent--hydrogen--is to be produced. Candidate water-splitting processes encompass a range of possibilities including:

- Photic - direct photon-energy dissociation
- Thermal - direct thermal dissociation, or through thermochemical processes
- Electrical - viz., water electrolysis (an industrially mature process).

These processes are further discussed in later sections of this document (water electrolysis particularly). Significantly, the coproduct produced in most water-splitting processes is oxygen, also of interest to KSC since liquid oxygen is the leading oxidizer employed in rocket propulsion systems, uniquely so in hydrogen-fueled space-vehicle systems.

### Hydrogen Liquefaction

Finally, for KSC applications as a rocket propellant, the hydrogen (and oxygen) must be liquefied, i.e., the normal ambient-temperature gaseous form must be converted to its ultracold cryogenic liquid form. This is presently both a capital- and energy-intensive process, as will be described later. By conventional means, for example, hydrogen's liquefaction energy requires roughly one-third of hydrogen's heating value as a fuel. Fortunately, there are promising technological alternatives on the horizon, a prominent approach being magnetic refrigeration, as will be discussed.

### Baseline NFDLH<sub>2</sub> Production Needs

A nominal 10 million gallon/year NFD-hydrogen facility, as stipulated in the KSC terms-of-reference information (Reference 1-1), will be the nominal target-capability considered in the study. Accordingly, conceptual designs will be developed and analyzed for the attractive candidate NFDLH<sub>2</sub> production scheme at this stage. These will be addressed on a comprehensive, balanced screening of all feasible options basis. Figure 1-3 presents the previously-displayed (Figure 1-1) KSC LH<sub>2</sub> projected requirements in this context. The arrow denotes the 10 million gallon/year level of NFDLH<sub>2</sub> production to be considered (about 6 million pounds/year). A range-of-uncertainty consideration (dotted area) has been added for an arbitrary early-1984 point in time projection. This reflects roughly a factor-of-2 departure above and below the trendline.

The purpose here is to show that the 10 million gallon/year sizing (arrow) seems quite reasonable in the face of a rather wide LH<sub>2</sub> demand uncertainty range. In other words, the selection of this particular facility-size appears appropriate in the face of uncertainties. If the "high" demand trend occurs, more than one NFDLH<sub>2</sub> facility module of this size may be needed. If the "low" trend occurs, one such module may suffice for an extended period of time. Interestingly, the conservative (lower) envelope demarkation intersects the (vertical) 1987 line, probably the earliest feasible plant-availability point, at about the 10 million gallon/year level.

### Basic System Requirements and Interfacing

As shown in Figure 1-4, the general system concept evaluated in this study uses non-fossil energy resources (nuclear, solar, geothermal) to produce liquid hydrogen for KSC utilization as a space vehicle fuel. In most cases, coproduct liquid oxygen is available as well from the basic water-splitting reactions involved. The basic system requirements characterizing the evaluated systems were:

- 10 million gallons/year LH<sub>2</sub>: about 18 STS launches/year
- Sufficient LO<sub>2</sub> coproduct
- Stand-alone basis, i.e., no utility interconnect (such was examined however)

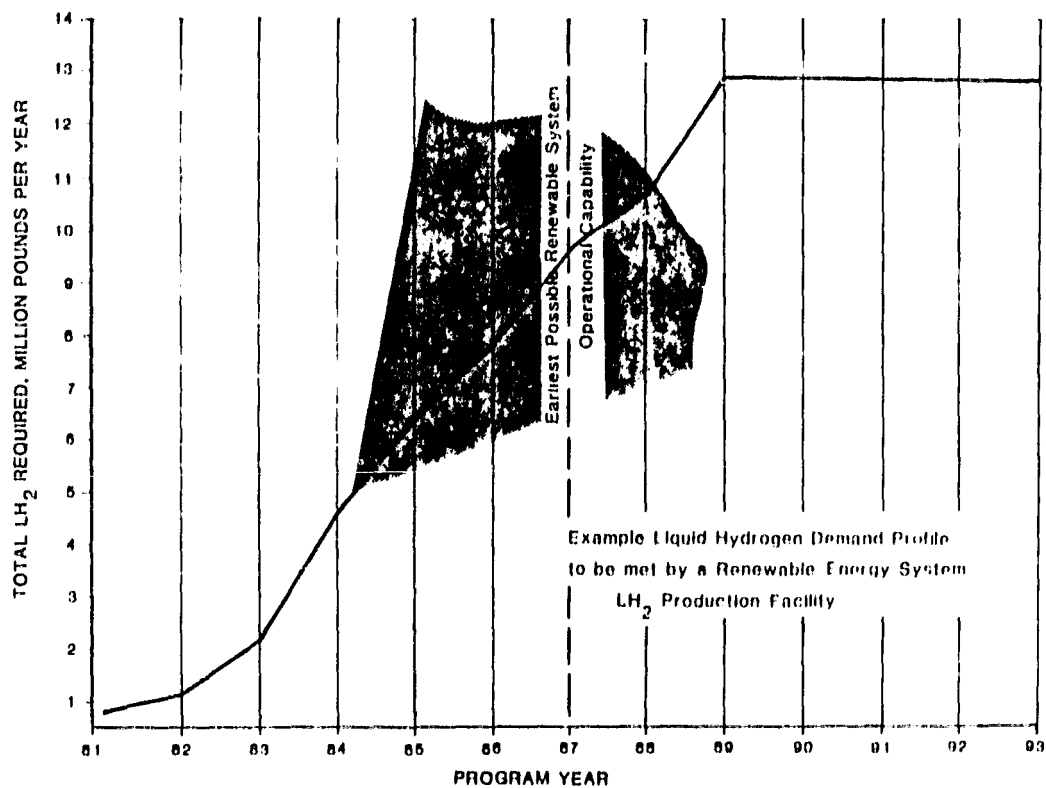


Figure 1-3. KSC LH<sub>2</sub> REQUIREMENT PROJECTION SHOWING THE EFFECT OF UNCERTAINTY IN TIMING/SIZING OF NFDLH<sub>2</sub> SOURCES

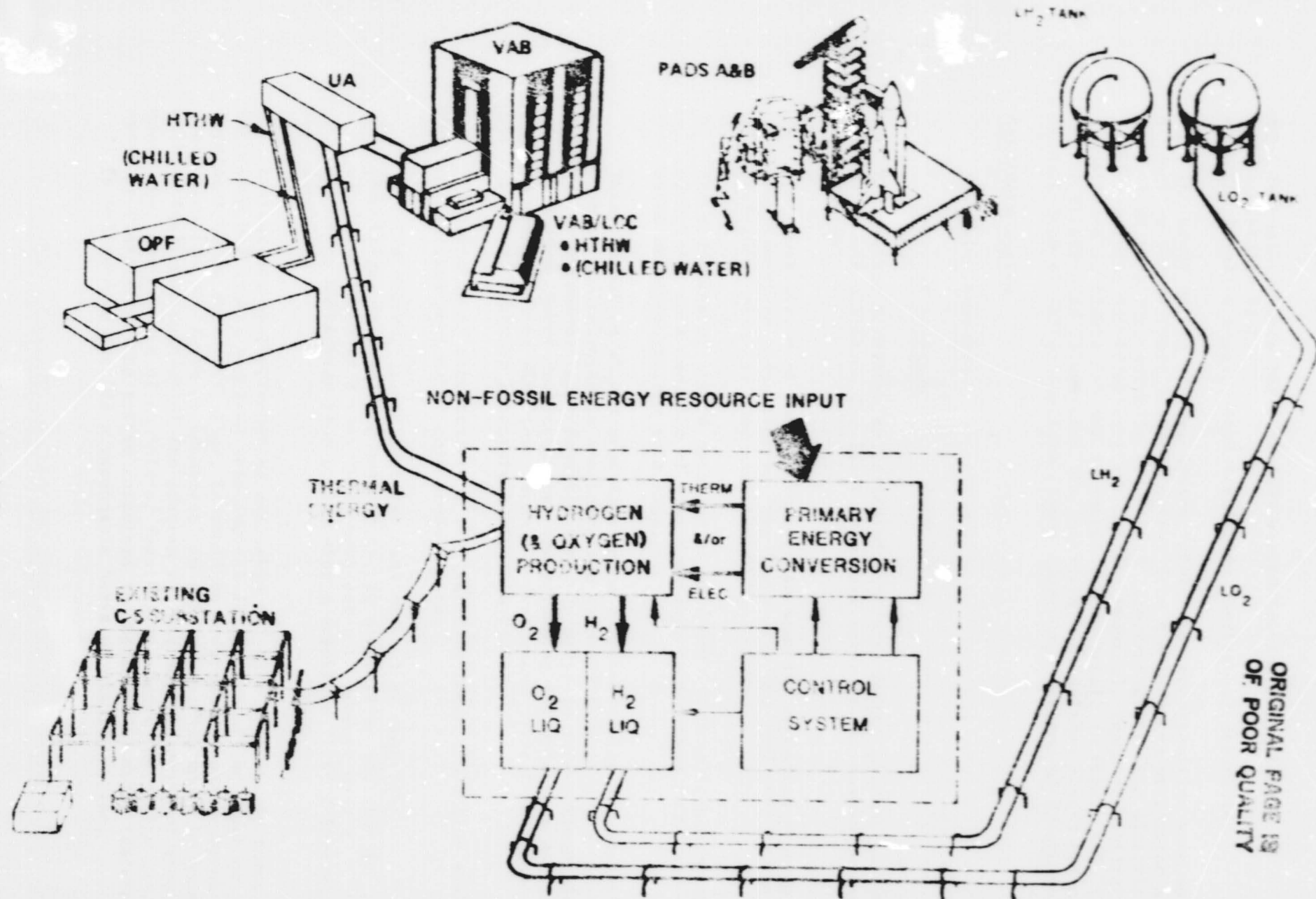


Figure 1-4. NON-FOSSIL HYDROGEN PRODUCTION SYSTEM  
CONCEPT

- Technology/costs for 1987-1992 period initial operational capability (IOC)
- KSC location (e.g., local insolation conditions) desirable.

The study was to address system interfacing opportunities such as the productive use of thermal energy output from the hydrogen production system, as well as possible, mutually beneficial interfacing with the electric utility serving KSC (Florida Power & Light Company). These possibilities are illustrated in Figure 1-4 and in somewhat more detail in Figure 1-5. The latter figure also illustrates the opportunity to deliver liquid hydrogen product from off-site locations (lower right-hand portion of Figure 1-5).

#### Candidate System

##### Screening Approach

##### Logic of Approach

A two-stage screening/selection of candidate NFDLH<sub>2</sub> production system candidates was utilized. The first screening criteria set was concerned with establishing:

1. The capabilities of each technology to meet the technical program requirement as a function of time-frame from the 1987-1992 to the post-2000, earliest need time period.
2. The economics of liquid hydrogen as produced by these technologies, especially as a function of time from 1987 to the year 2000, and--where possible--beyond this time.

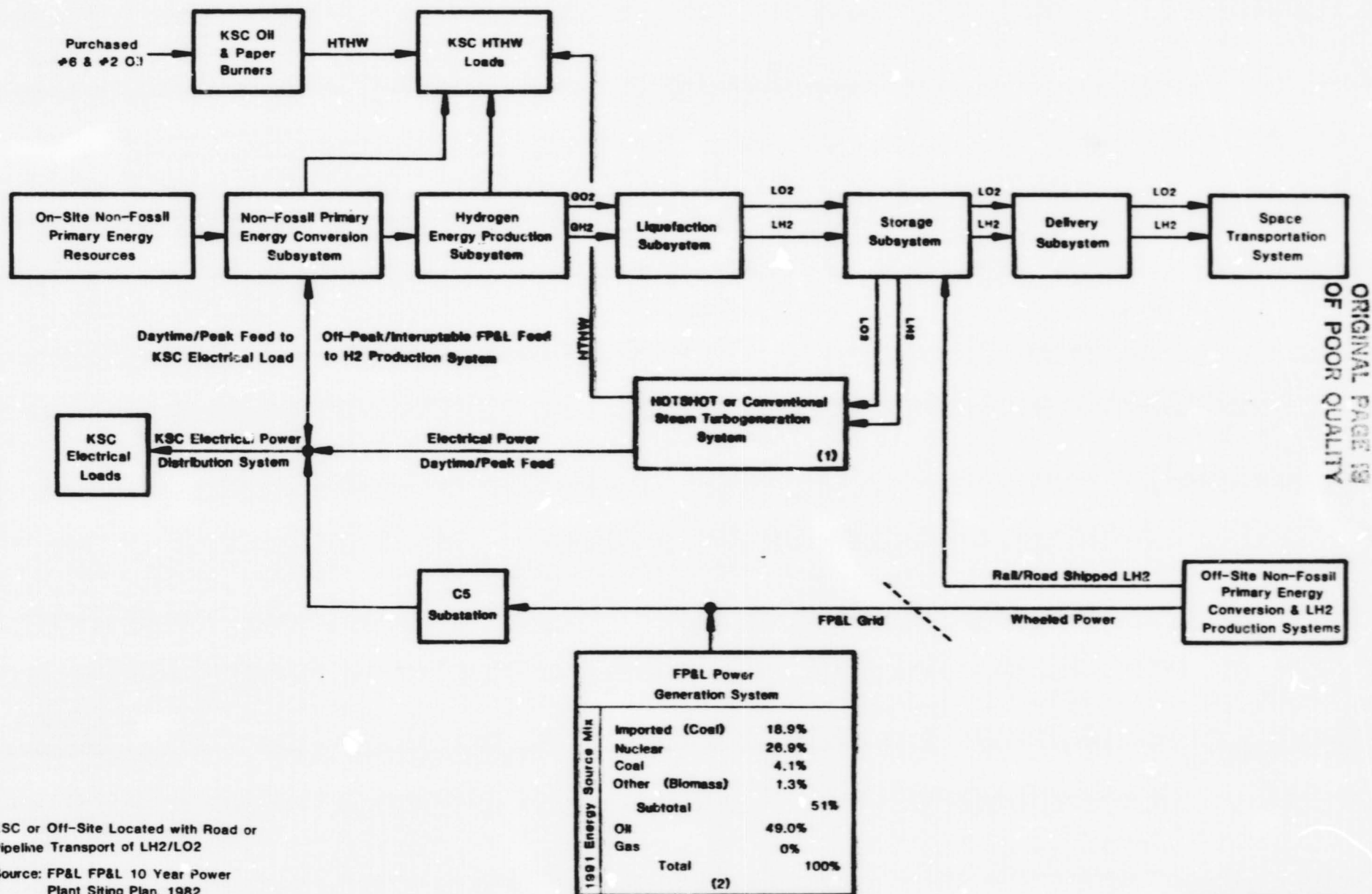
This evaluation should provide a means of establishing the capability of the screened technologies in consideration to contribute to producing liquid hydrogen at an economically feasible cost. In order to take maximum advantage of work done by other investigators, the screening criteria were designed for maximum compatibility with the "Technical Assessment Guide," published by the Electric Power Research Institute (Reference 1-3).

The operational requirement of the liquid hydrogen production system is defined, for the purpose of this study, to be:

"To deliver liquid hydrogen (and oxygen) of specified properties, in specified quantities, to a specified location at specified times at a contracted cost per unit product over a specified multi-year time period with a specified first delivery date."

Limitations on the resources available for this project, in terms of both time and money, required some logical limitation of the depth of treatment to be attempted. Thus, it would be desirable to use a system of classification of "depth of treatment" in this study that would be compatible with logical continuation of the program so long as this depth of treatment meets the requirements of an initial feasibility study. The Design and Cost Estimate Classifications system contained in the EPRI TAG mode! (Reference 1-3) is believed to provide a reasonable basis of classification.



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(1) KSC or Off-Site Located with Road or Pipeline Transport of LH<sub>2</sub>/LO<sub>2</sub>

(2) Source: FP&L FP&L 10 Year Power Plant Siting Plan, 1982

Contract NAS10-10541  
Dec 1982 RWF

Figure 1-5. NON-FOSSIL ENERGY BASED HYDROGEN (AND OXYGEN) PRODUCTION SYSTEM (SUBSYSTEM'S OPTIONS INTERCONNECT)

## General Discussion of the Design and Construction Process in Relation to New Technologies

It is assumed, for example, that prior to award of a design contract to an appropriate organization, all feasibility studies have been completed and that the basic system concept has been selected. The owner has also defined all major project objectives and constraints and identified a time-frame and budget. It is also assumed that the design process is more or less typical, i.e., that an adequate experience base exists to support actual design and construction. No research, development, or other such activities should be undertaken. This carries a significant implication in selecting suitable technologies. It must be borne in mind that the experience base should also include sufficient construction experience so that the manpower requirement, special equipment requirement, time resources, and budgetary resources required for design and construction can be reliably estimated.

Prior to such an award, however, there are a number of major milestones which may have to be met. The need for, and impact of, such milestones is significantly dependent upon the specific technology to be employed. These milestones and the design process itself can be placed in the context of Screening Criteria and deserves specific consideration. Table 1-2 provides a basis for this (from Reference 1-3).

The design/construction process in question is very dependent upon the status of the technology option selected. Viewed from this perspective, the design/construction process is suggestive of certain screening criteria-related subjects applicable to the project under study, for example:

- The level of commercial maturity of the selected technology option: If it is assumed that the necessary equipment will be commercially available for any option selected, some technologies are more mature than others. When necessary equipment is only available in a prototype stage, there is an increased risk of redesign due to equipment modification or substitution. Furthermore, if system implementation calls for a construction process with which contractors are not familiar, they will tend to escalate their quotes due to a perceived risk.
- The complexity of the design/construction process: This impacts both time and cost in all phases of work. Special sequencing during construction or interim testing may also be necessary in direct proportion to such complexity, further complicating the process.
- The actual amount of implementation task required: Different technologies will require different amounts of facility-construction work. This has a time and cost impact on the construction work.
- The ease and degree to which the performance, maintainability, and reliability of a given system can be predicted and subsequently verified in the field.
- The lead-time required for equipment.

Table 1-2. DESIGN AND COST ESTIMATE CLASSIFICATIONS  
(Source: Reference 1-3)

Item	Design/ Estimate Description	Project Contingency Range	Design Information Required	Cost Estimate Basis		
				Major Equipment	Other Materials	Labor
Class I	Simplified	30%  to  50%	General site condition, geographic location & plant layout.  Process flow/operation diagram.  Product output capacities.	By overall project or section-by-section based on capacity/cost graphs, ratio methods, and comparison with similar work completed by the contractor, with material adjusted to current cost indices and labor adjusted to site conditions.		
Class II	Preliminary	15%  to  30%	As for Type Class I plus engineering specifics, e.g.:  Major equipment specifications.  Preliminary P&I flow diagram.	Recent purchase costs including freight) adjusted to current cost index.	By ratio to major equipment costs on plant parameters.	Labor/material ratios for similar work, adjusted for site conditions and using expected average labor rates.
Class III	Detailed	10%  to  20%	Complete process design. Engineering design usually 20%-40% complete. Project construction schedule. Contractural conditions and local labor conditions.	Firm quotations adjusted for possible price escalation with some critical items committed.	Firm unit cost quotes (or current billing costs) based on detailed quantity take-off.	Estimated man-hour units (including assessment) using expected labor rate for each job classification.
Class IV	Finalized	5%  to  10%	As for Class III, with engineering essentially complete.	Pertinent taxes & freight included.  As for Class III, with most items committed.	As for Class III, with material on approximately 100% firm basis.	As for Class III, some actual field labor productivity may be available.

There are also a number of enabling-factors or "milestones" which may have to occur prior to initiation of the final facility implementation effort. As these milestones are also technology-dependent, they may also be viewed as possible screening criteria inputs. Such milestones include:

- The need for obtaining approval from local code officials (if on non-federal land). Compliance with the appropriate sections of the locally-accepted fire, building, and electrical codes would be required. Interpretation of such codes may pose a problem if these codes do not specifically address the selected technology. Compliance with any corresponding state or local standards would be required if on public land.
- The need for demonstrating compliance with air-quality, water, thermal, and/or safety standards. Such standards may be tied to a combination of federal, state, or local criteria. Definition of just what standards should be applied, particularly to a "new" or "advanced" technology, may in itself be a problem.
- The possible need for special permits (or their equivalent) if a regulated natural resource, e.g., ground water, river water, wildlife refuge, etc., were to be consumed or otherwise impacted.

#### References Cited in Section 1

- 1-1. Solicitation No. 10-3-0068-2, "Study of Systems and Technology for Hydrogen Production Independent of Fossil Fuels," by the John F. Kennedy Space Center, NASA, solicitation issued 13 May 1982.
- 1-2. Solicitation No. 10-2-0150-2, "Polygeneration Feasibility Study," by the John F. Kennedy Space Center, NASA, solicitation issued 9 August 1982.
- 1-3. Report No. P-2410-SR, "Technical Assessment Guide," by the Electric Power Research Institute, Palo Alto, CA, May 1982.

## 2. CHARACTERISTICS OF KSC UTILITIES/LOADS

### Electrical

#### Demand/Consumption

Peak electrical demand has been monitored at NASA-KSC, as reported by Florida Power & Light Company (FPL) on a 15-minute basis for both the C-5 and Orsino on-site substations at KSC (Figure 2-1). This power demand, is shown in Table 2-1 (Reference 2-1), along with projected demand and consumption for 1988. The historic monthly variation in demand is represented in Figure 2-2. It can be expected that the instantaneous demand may be somewhat larger than the 15-minute demand reported here. However, no data is available to suggest the magnitude of this variation.

Table 2-1. HISTORICAL AND PROJECTED KSC ELECTRICITY DEMAND AND CONSUMPTION  
(Reference 2-1)  
FY'81 - HISTORICAL

<u>Substation</u>	<u>Load Data (MW)</u>		<u>Energy Data (MWH)</u>
	<u>Minimum</u>	<u>Maximum</u>	
Orsino	3.9	16.6	77,628
C-5	5.8	15.6	88,242
TOTALS	9.7	32.2	165,870

#### FY'88 - PROJECTED

<u>Substation</u>	<u>Load Data (MW)</u>		<u>Energy Data (MWH)</u>
	<u>Minimum</u>	<u>Maximum</u>	
Orsino	4.1	17.4	87,354
C-5	6.4	17.2	106,766
TOTALS	10.5	34.6	194,120

#### Service Location and Capacity

KSC is supplied electrical power by a 115-kV loop from FPL. The utility service lines connect to the KSC 13.8-kV underground and overhead distribution system via two major substations--C-5 at the Vertical Assembly Building (VAB) and Orsino at the NASA Industrial Area as shown in Figure 2-1. This FPL service has a capacity of approximately 58-MW based on the service-line size. KSC maintains five 1-MW diesel-driven generators adjacent to the C-5 substation in addition to several smaller, dispersed and/or mobile generators for use in the case of commercial power outages. The transmission capacity of the KSC 13.8-kV system is approximately 50-MW.

### Thermal

#### Heating

There are two major thermal load centers at KSC--the KSC Industrial Area and the Utility Annex (UA). The heating thermal requirements of each area are

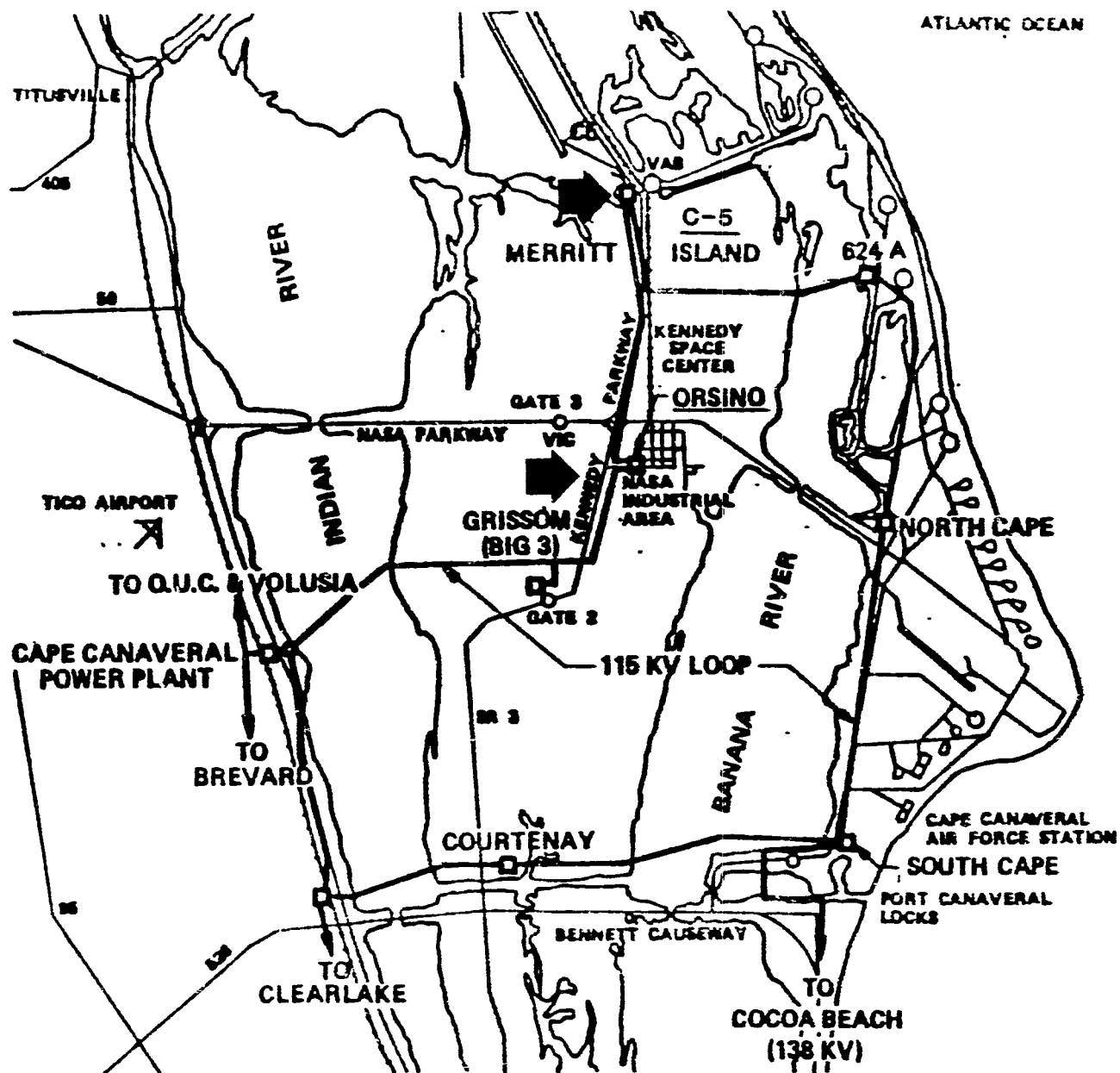


Figure 2-1. KSC ELECTRICAL DISTRIBUTION AND FPL SERVICE LINES

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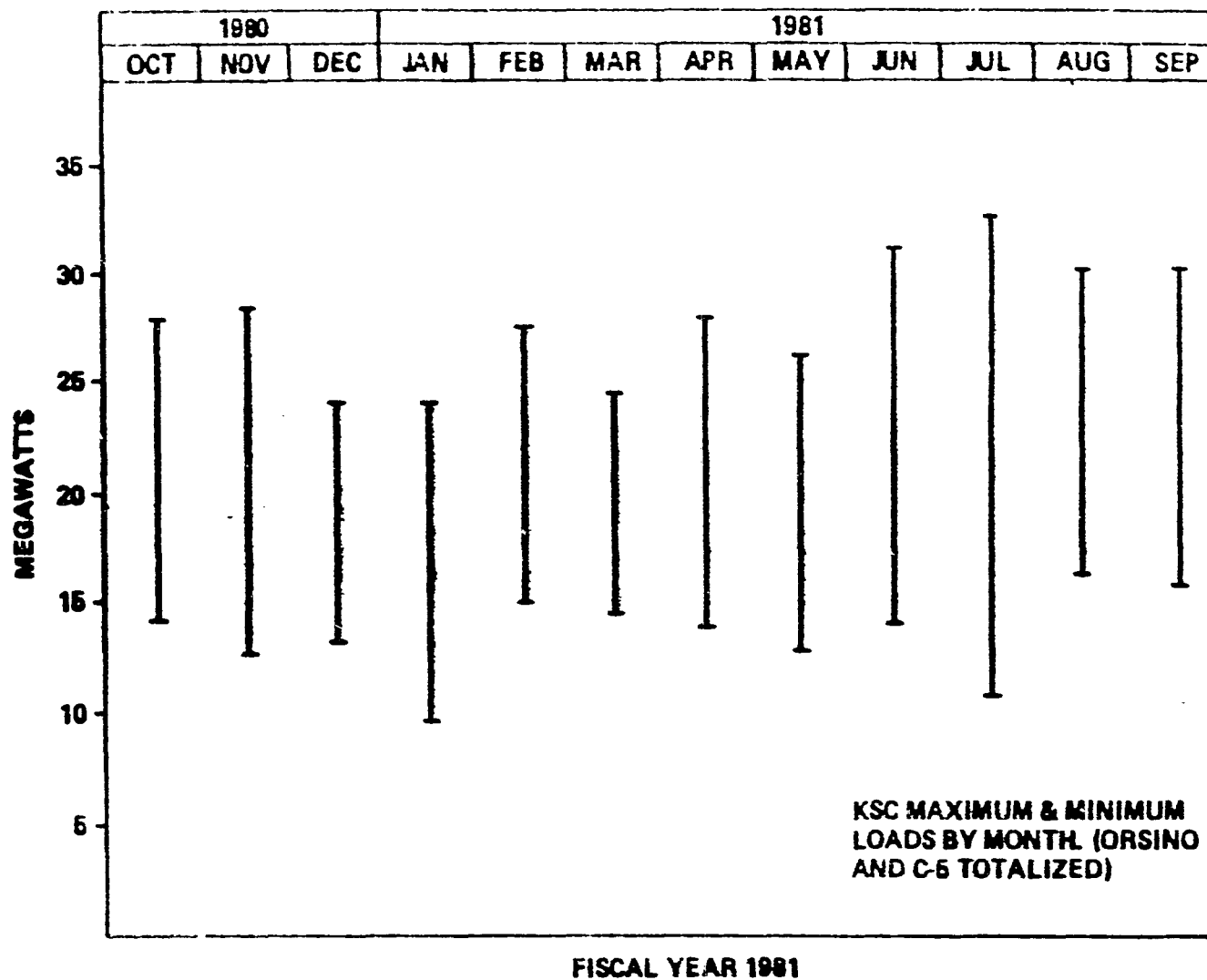


Figure 2-2. MONTHLY VARIATION IN TOTAL ELECTRICITY DEMAND  
(Source: Reference 2-1)

provided by central and distributed oil-fired, hot water boilers and small, distributed oil, electric, gas, and heat-pump heating systems. Table 2-2 shows a summary of the historic and projected oil-fired boiler thermal demand and consumption figures for the KSC Industrial Area Central Heating Plant (CHP) and the UA.

Table 2-2. HISTORIC AND PROJECTED UA AND CHP THERMAL HEATING DEMAND AND CONSUMPTION BASED ON OIL CONSUMPTION  
(Reference 2-1)

KSC Load Center	Demand Range (MW)		Consumption (MWH)	
	1981	1986	1981	1986
UA	1.4-4.7	1.8-5.9	$24.1 \times 10^3$	$30.3 \times 10^3$
CHP	2.9-6.3	3.6-8.0	$29.8 \times 10^3$	$37.5 \times 10^3$

At the KSC Industrial Area, the CHP has two oil-fired, 11.7-MW (40,000,000 Btu/hr) boilers and one oil-fired, 4.7-MW (16,000,000 Btu/hr) boiler that provide 325°-400°F hot water via high-temperature, hot water (HTHW) above- and below-ground piping to the buildings and processes in the KSC Industrial Area. A small percentage of the total Industrial Area heating requirements are provided by small, distributed oil-fired boiler, electric, gas, and heat-pump systems as shown on the KSC Master Plan Industrial Area Heat Distribution Drawing VIII-2, Sheet 3. A small solar thermal system provides hot water to the HQ cafeteria and film lab. The remote hypergol Maintenance Facility and Vertical Processing Facility at the Industrial Area are both served by a low-temperature, hot water loop from a nearby boiler. A waste-paper incinerator is currently under construction in the Industrial Area that is rated to supply up to 5.1-MW to the HTHW loop.

At the VAB Utility Annex (UA), the other major thermal heating load center, there are three 4.7-MW boilers in a central HTHW (325°-400°F) generating plant to serve most of the buildings and processes immediately adjacent to the VAB. The distribution piping from these boilers is restricted to the area immediately adjacent to the VAB. The oil-fired thermal heating loads are summarized in Table 2-3. Figure 2-3 shows the monthly variation in UA thermal heating demand. The balance of the VAB UA building heating thermal loads are served by small, distributed, oil-fired boiler, electric, gas, and heat-pump systems as shown on the KSC Master Plan Launch Complex 39 Area Heat Distribution (Drawing VIII-2, Sheet 4).

Table 2-3. VAB UA CENTRAL CHILLED WATER PLANT THERMAL LOAD

Range of Demand (MW)		Consumption (MWH)	
1981	1986	1981	1986
3.5-12.0	4.4-15.1	54,300	68,400

### Cooling

A total of nearly 87.9-MW (25,000 tons) of cooling capacity is installed at the KSC facility. In the Industrial Area, where there is no central chilled water plant, individual installations ranging from 6.3-MW to 19.7-MW capacity provide chilled water to the O&C, CIF, and HQ buildings. Smaller centrifugal and reciprocating machines are dispersed throughout the Industrial Area.



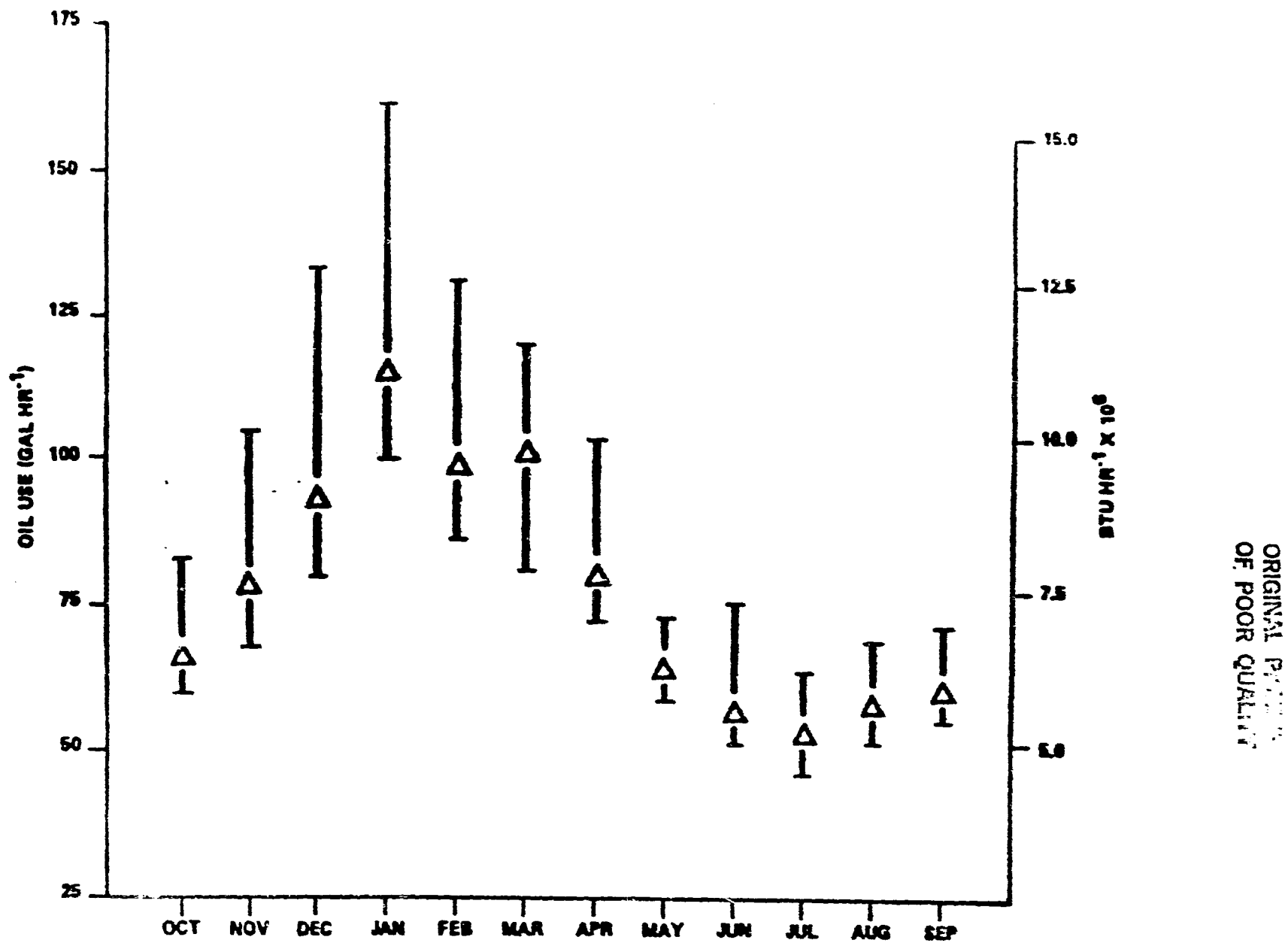


Figure 2-3. UTILITY ANNEX MONTHLY HEATING THERMAL DEMAND FOR THE YEAR 1981  
(Source: Reference 2-1)

At the UA, a central centrifugal chilled water plant with a rated capacity of 35-MW provides chilled water via a distribution system to the OPF, VAB, and LCC. Four separate chiller systems are maintained for launch-critical computer cooling. The historic range of monthly chilled water thermal demand is shown in Figure 2-4 and the historic range of monthly total (heating + cooling) thermal demand is shown in Figure 2-5.

### Hydrogen

The major use of hydrogen at KSC is for Shuttle fueling operations. Each Shuttle launch requires approximately 386,000 gallons of liquid hydrogen. Liquid hydrogen is stored in 850,000-gallon, vacuum-insulated spherical dewars located adjacent to each pad. Liquid hydrogen is currently trucked from New Orleans and loaded into the dewar immediately prior to a launch operation. It is estimated that daily boil-off losses amount to approximately 1,200 gallons/day (710 pounds/day) while losses during transfer from the dewar to the Shuttle (which is accomplished by pressure transfer through underground piping) are approximately 100,600 gallons. These figures, combined with additional losses anticipated in transferring hydrogen, suggest a peak 41,000 gallons/day (24,000 pounds/day) liquid hydrogen demand corresponding to a launch rate of 24 launches/year (Reference 2-1). For a full year, this would correspond to about 15 million gallons/year; however, per the originating KSC study-solicitation, the liquid hydrogen demand addressed in this study was 10-million gallons/year, or 5.9 million lb/year.

### Oxygen

The largest use of liquid oxygen at KSC is also for Shuttle Fueling operations. Each launch requires 144,400 gallons. Liquid oxygen is stored in 900,000-gallon, vacuum-insulated dewars located in two launch complexes. It is estimated that daily boil-off losses amount to approximately 2,700 gallons/day (25,700 pounds/day) while losses during transfer are approximately 48,600 gallons (463,000 pounds). At a maximum launch rate of 24 launches/year, the resulting liquid oxygen demand will be 18,000 gallons/day (169,000 pounds/day) (Reference 2-1). Liquid oxygen, as viewed in this study, is a valued coproduct of hydrogen production from water "feedstock." In this, more than a matching amount of oxygen is produced for a given hydrogen yield, for space-vehicle usage purposes.

### Water

KSC potable water is purchased from the nearby city of Cocoa. The current consumption is approximately 400,000 gallons/day and is not expected to exceed 650,000 gallons/day during launch operations (Reference 2-2). In both the UA and Industrial Area, there are 250,000-gallon, elevated tanks and 1,000,000-gallon, in-ground tanks as well as fire pumps and wells for fire supply. Potable and fire distribution piping is provided throughout the facility as indicated on the KSC Master Plan Water Distribution Drawings VIII-3, Sheets 3 and 4.

To produce hydrogen and oxygen sufficient to meet projected Shuttle demands, less than 30,000 gallons of water/day would be electrolyzed. This water demand represents less than a 5% increase in projected KSC water demand.

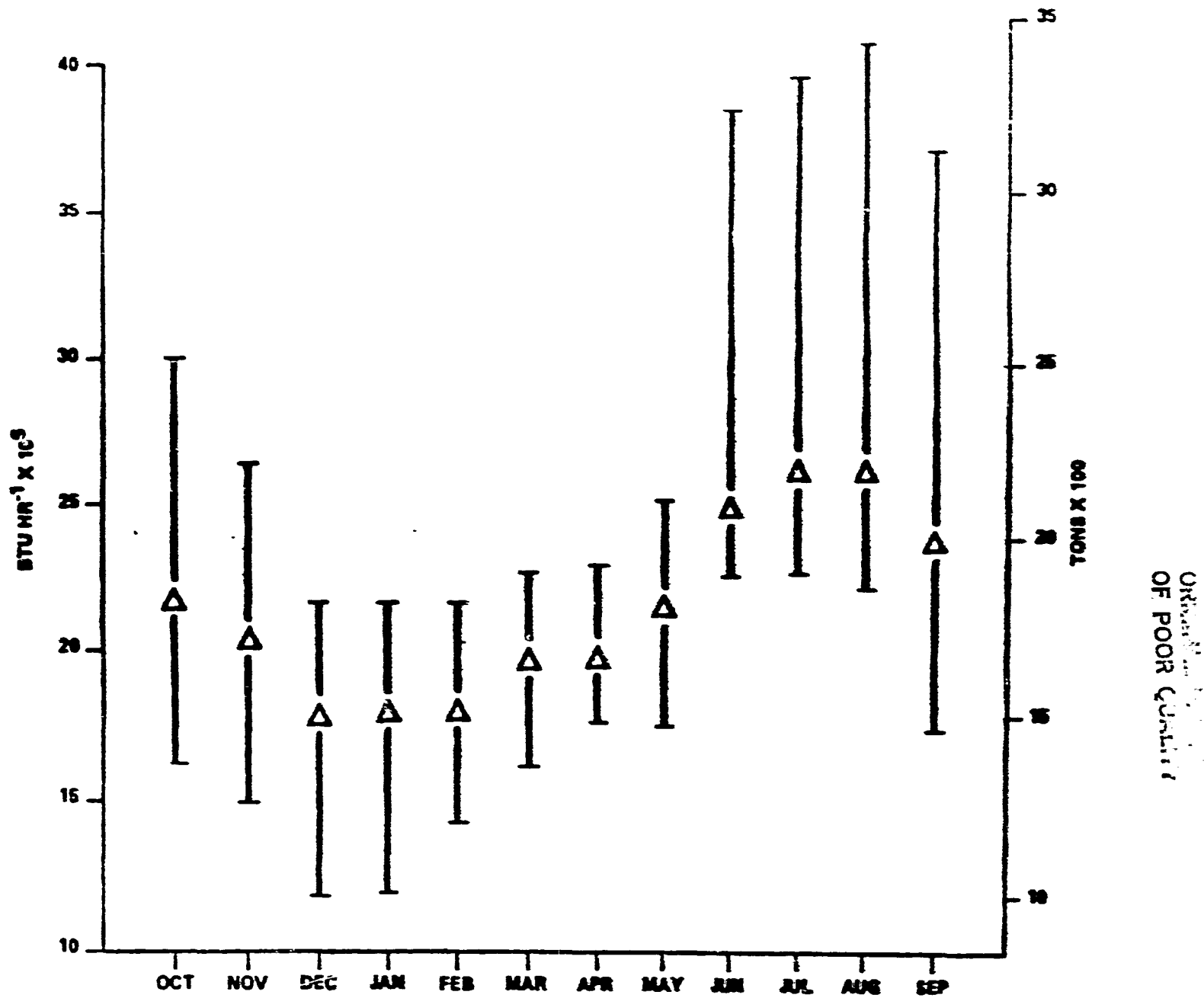


Figure 2-4. UTILITY ANNEX MONTHLY CHILLED WATER THERMAL LOAD  
(Source: Reference 2-1)

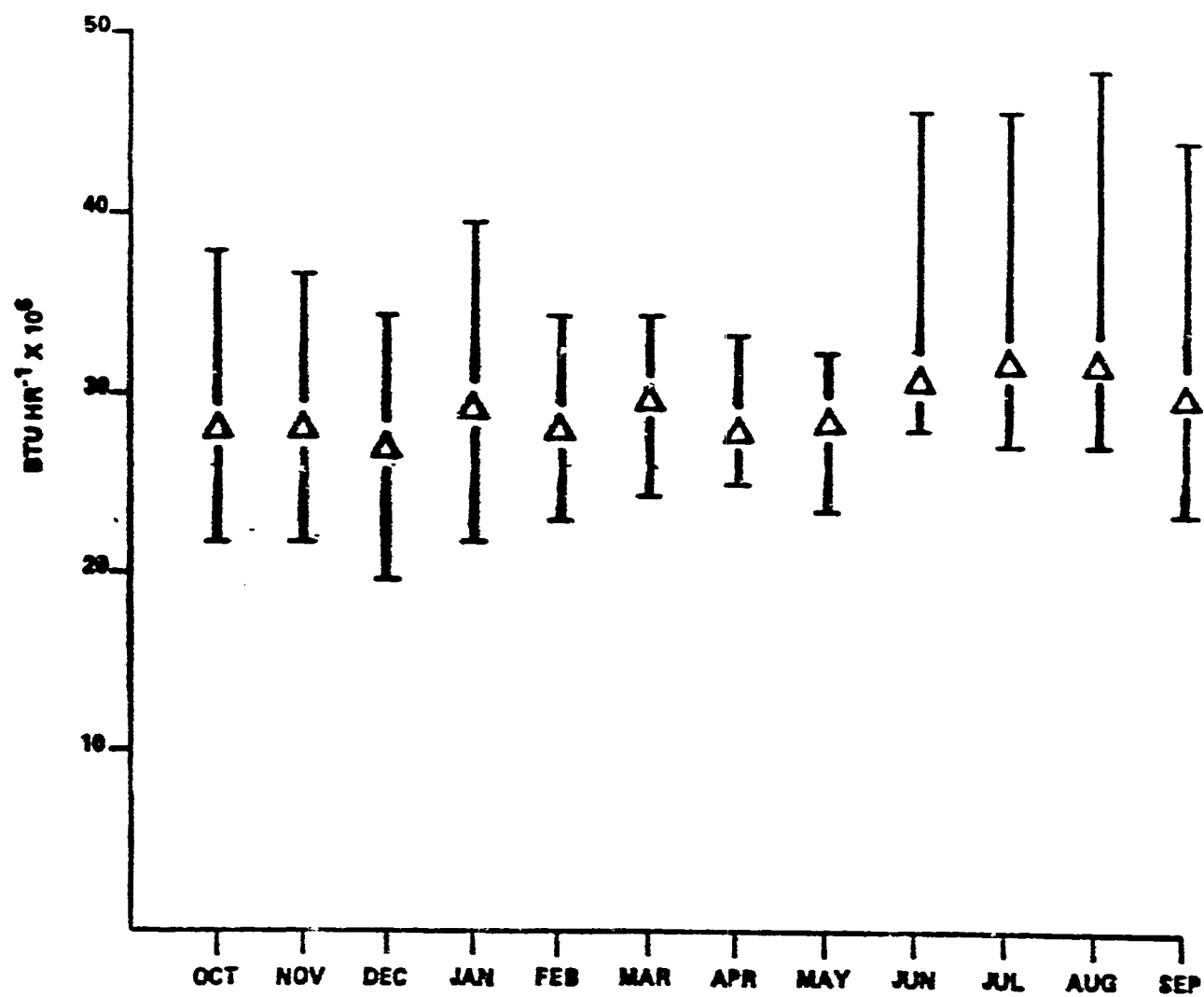


Figure 2-5. UTILITY ANNEX MONTHLY TOTAL HEATING AND CHILLED WATER LOAD  
(Source: Reference 2-1)

## Utility of Coproducts

The purpose of this section is to determine the utility at KSC of coproducts of the proposed non-fossil hydrogen system. The major possible coproducts--electricity, oxygen, and thermal energy--are discussed separately below. Background data on KSC electricity and thermal energy consumption is presented in earlier sections. For background data on KSC launch-dependent and base fuels and liquids use, an inventory is provided here. Tables 2-4 and 2-5 provide a summary of Space Transportation System (STS) fuels and liquids as well as Expendable Launch Vehicle (ELV) fuels and liquids. In addition to providing a summary of quantities required per launch, these tables show the base KSC consumption for possible coproducts: liquefied- and gaseous-oxygen, hydrogen, and nitrogen.

Note that the Base Annual (BA) quantities are independent of any launches as explained in the notes to the table. This quantity would be consumed even with no launches within the year.

### Electricity

Any electricity-producing, non-fossil hydrogen system developed at KSC could provide electricity to the FPL feeder loop or directly to the KSC electricity distribution system e.g., to offset KSC electricity consumption. (Note: It is not clear now what reception this concept would have at FPL and this should be the subject of discussions prior to further, more-detailed engineering analysis.) For a KSC direct current power generating system, e.g., photovoltaic generators, an inverter and appropriate power conditioning and safety equipment would be required between the power generating system and the KSC or FPL lines. It is anticipated that, at times, "surplus" power available may exceed the KSC demand; in that case, excess power could be provided to the FPL grid. In such cases, the current carrying capacity of the FPL feeder may be the factor that limits the extent of power "sellback" possible.

In addition to the FPL "sellback" option, excess electricity could be used to produce and compress gaseous nitrogen ( $\text{GN}_2$ ). KSC currently purchases gaseous nitrogen from the Big Three  $\text{GN}_2$  Air Separation Plant located near Gate 2 at the south end of the KSC facility. Gaseous nitrogen is piped at 6,000 psi through an extensive pipeline system to the Industrial Area, the VAB, and to Launch Area 39 as shown in Figure 2-6. The KSC base use of  $\text{GN}_2$  is approximately 986,000 SCF/day, while peak Shuttle requirements are projected to be an additional 2,667,000 SCF/day--resulting in a projected total  $\text{GN}_2$  demand of 3,653,000 SCF/day.

### Oxygen

An electrolyzer operating to provide the projected demand of 24,000 pounds/day of hydrogen will coproduce 192,000 pounds/day of oxygen. Although the KSC facility has no great demand for gaseous oxygen, this oxygen could be liquefied and used to provide the Shuttle projected liquid oxygen demand of 169,000 pounds/day. Surplus liquid oxygen may be used as fuel for the Atlas-Centaur and Delta 2900 Series and 3900 Series expendable launch vehicles.

### Thermal

Coproduced hot water from the non-fossil hydrogen system could be in the range of 150°-200°F as rejected heat from the electrolyzer and at somewhat

Table 2-4. SPACE TRANSPORTATION SYSTEM FUELS AND FLUIDS

Fluid	Use	1/ OBQ	2/ B-D	3/ BA	Unit
Liquid Hydrogen (LH <sub>2</sub> )	Propellant for ET; reactant for fuel cell Vehicle boiloff; loading losses; conversion to GH <sub>2</sub> Quiescent boiloff	102,513	44,588	137,894	kg kg kg
Liquid Oxygen, High Purity (LO <sub>2</sub> ) (LAir = Liquid Air)	Propellant for ET Vehicle boiloff; loading losses; and LAir LAir for SCAPE; quiescent boil-off of Dewars	609,638	417,312	3,447,360	kg kg kg
Liquid Oxygen, Fuel Cell Grade (LO <sub>2</sub> )	Fuel cell (reactant and ECLSS) Conversion to GO <sub>2</sub> for fuel cell purge; FSS servicing; transfer/loading losses	1,361	11,340		kg kg
Gaseous Helium (GHe)	ET, RCS, APU, OMS pressurant; APU pressurant for each SRB Purging, leak checking, and inerting General support (purging, leak checking, inerting)	510	20,957	77,880	kg kg kg
Gaseous Nitrogen (GN <sub>2</sub> )	ECLSS atmosphere diluent, hydraulic system accumulator pressurant; SRB hydraulic system accumulator pressurant Purging, leak check, inerting, and drying agent General support (purging, leak check, inerting, etc.)	85	104,784	2,180,640	kg kg kg

Table 2-4, Cont. SPACE TRANSPORTATION SYSTEM FUELS AND FLUIDS

Fluid	Use	1/ GBQ	2/ BLD	3/ BA	Unit
Liquid Nitrogen (LN <sub>2</sub> )	Standby for GN <sub>2</sub> pipeline; SCAPE support		73,483		kg
	Conversion to GN <sub>2</sub> ; SCAPE; quiescent boiloff			1,587,600	kg
Monomethylhydrazine (MMH)	Orbiter OMS and RCS fuel	5,366			kg
	Hypergol Training Facility			3,629	kg
Nitrogen Tetroxide (N <sub>2</sub> O <sub>4</sub> )	Orbiter OMS and RCS	7,873			kg
	Hypergol Training Facility			5,443	kg
Hydrazine (N <sub>2</sub> H <sub>4</sub> )	Orbiter and SIB APS fuel	327			kg
Mixed oxides of nitrogen (MON-10)	Enrichment of NO content of N <sub>2</sub> O <sub>4</sub>	907			kg
Freon 113	Pad Hypergol oxidizer system flush; SCAPE flush		23,950		kg
	General cleaning			498,960	kg
Isopropyl Alcohol	Pad hypergol fuel system flush		45,420		liter
	General cleaning support			7,570	liter
Ammonia	Orbiter coolant loop	68			liter
FC-40	Orbiter fuel cell coolant (scheduled maintenance)	45			kg
	Scheduled maintenance (twice yearly per Orbiter)			272	kg

Table 2-4, Cont. SPACE TRANSPORTATION SYSTEM FUELS AND FLUIDS

Fluid	Use	1/ OBO	2/ BLD	3/ BA	Unit
Freon 21	Orbiter radiator coolant loop Sample Scheduled maintenance (once a year per Orbiter)	227	5	680	kg kg kg
Demineralized Water (DM)	SRB flush Cleaning solvent (component cleaning lab)		75,700	7,570,000	liter liter
Hydrochloric Acid (HCl)	Regenerant to produce DM Regenerant to produce DM		151	13,248	liter liter
Sodium Hydroxide (NaOH)	Neutralizing agent (Freon); regenerant (DM) Regenerant to produce DM		1,098	11,734	liter liter
Potable Water (Crew)	Purchased drinking water for crew	45			liter
Coolant Water	ECLSS and APU (scheduled maintenance) Scheduled maintenance (twice yearly per Orbiter)	314		681	liter liter
Carbon Dioxide (CO <sub>2</sub> )	For charging annulus ET GH <sub>2</sub> vent line		TBD		
Diesel Fuel	For operating five Paul rechargers			45,420	liter
Hydraulic Fluid	Hydraulic systems Scheduled maintenance	450		2,725	liter liter



Table 2-4, Cont. SPACE TRANSPORTATION SYSTEM FUELS AND FLUIDS

Fluid	Use	1/ OBQ	2/ BLD	3/ BA	Unit
Halon 1301	Fire extinguishing agent Fire extinguishing agent	45		5,443	liter kg
Argon	Welding and brazing			4,361	m <sup>3</sup>
Propane	Firing CH <sub>2</sub> Various shops		1,135	45,420	liter liter

#### NOTES

- 1/ OBQ = Onboard quantity. This column lists the quantities of fluids required onboard the Space Shuttle at launch.
- 2/ BLD = Base launch dependent. This column lists the quantities of fluids required at the various Space Shuttle ground facilities to prepare the vehicle for launch.
- 3/ BA = Base annual. This column lists the total annual quantities of fluids required to support ground activities on a day-to-day basis, regardless of launch schedules.

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Table 2-5. EXPENDABLE LAUNCH VEHICLE FUELS AND FLUIDS

Substance	Unit	Delta		Atlas-Centaur	
		Base/Month <sup>1/</sup>	Amt/Launch <sup>2/</sup>	Base/Month <sup>1/</sup>	Amt/Launch <sup>2/</sup>
Aerozine -50	kg		1,814		
Gaseous Nitrogen	m <sup>3</sup>	1,416	2,832	235,031	566,340
Gaseous Helium	m <sup>3</sup>	1,416	4,248	16,990	33,980
Liquid Hydrogen	kg			4,436	7,257
Liquid Nitrogen	metric tons	45	73	14	82
Liquid Oxygen	metric tons	18	91	45	272
RP-1 (Highly Refined Kerosene)	kl		32		57
Nitrogen Tetroxide	kl		2,858		
Hydrogen Peroxide	kg			408	

<sup>1/</sup> Base/month. This column lists the total monthly quantities of fluids required to support ground activities on a day-to-day basis, regardless of launch schedules.

<sup>2/</sup> Amt/launch. This column lists the quantities of fluids required to accomplish the launch of the specified ELV.

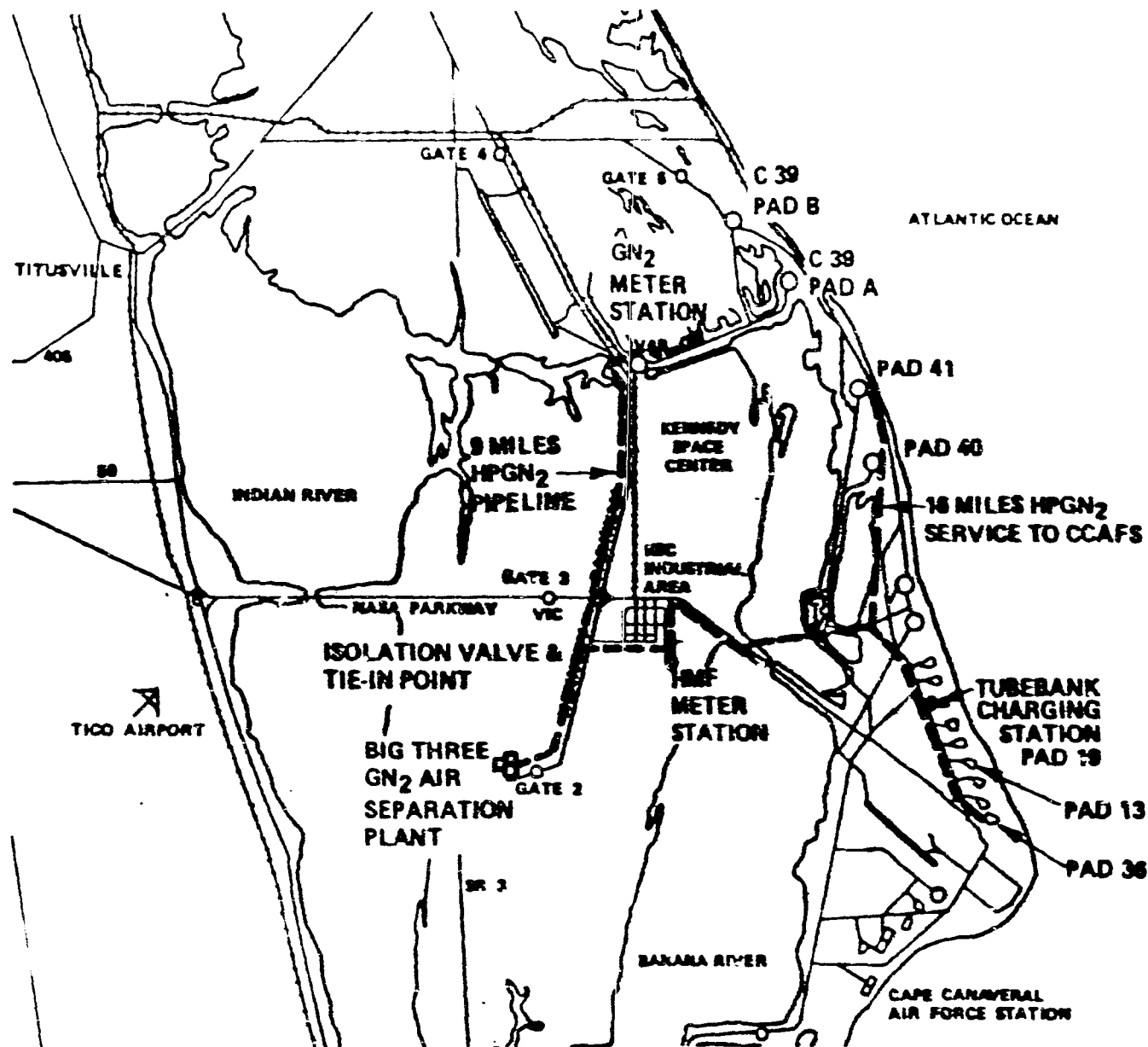


Figure 2-6. GN<sub>2</sub> CROSS-COUNTRY PIPELINE

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higher temperatures from a nuclear or solar thermal electric plant. However, it is not expected that any thermal energy coproduced by the non-fossil hydrogen system would be very useful to the Industrial Area due to the following factors:

- The waste paper incinerator currently under construction is sized to provide most of the HTHW thermal energy demand.
- The Industrial Area does not have a central chilled water plant. In order to utilize coproduced thermal energy for cooling at the Industrial Area, the installation of distributed- or central-absorption chillers and a hot- or chilled-water loop would be required at considerable expense.

It is expected, however, that coproduced thermal energy would have some utility at the UA at the VAB. This is because the VAB UA utilizes a central HTHW heating plant which serves substantial year round loads that are relatively localized in three buildings. Coproduced heat from a non-fossil hydrogen production system could be used in the HTHW loop and/or to drive a central absorption chiller plant to meet UA cooling loads. It is possible that low-temperature hot water from the electrolyzer could be used directly to drive an absorption chiller or could act as a heat source for a high-temperature industrial heat-pump to provide 400°F water for the HTHW piping loop.

References Cited in Section 2

- 2-1. RFP No. 10-2-0150-2, "Polygeneration Feasibility Study," issued by the John F. Kennedy Space Center, NASA, issued 9 August 1982; also selected portions of "Coal Gasification - Polygeneration System for KSC/LC-39," by G. Gutkowski, KSC Design Engineering Directorate, March 1982.
- 2-2. "Environmental Impact Statement for the Kennedy Space Center (1978-1979 Revision)," Final Report prepared for the National Aeronautics and Space Administration, October 1979.

### 3. INTRODUCTION OF CANDIDATE TECHNOLOGIES AND SYSTEMS

This discussion serves principally to identify and categorize the options for a liquid hydrogen production system based on non-fossil primary energy resources. Detailed descriptions of each technology are contained in Reference 3-1 or in the Appendices. A brief description of each is presented in Section 6 where the technology is first screened.

#### Primary Energy Systems

There are four primary energy resources that may be used for the production of hydrogen. They are:

1. Fossil Energy Resources which provide both process energy and some of the feedstock material required. These resources include petroleum, natural gas, coal, oil-shale, and tar-sands.
2. Solar Energy Resources, both direct (e.g., photovoltaics) and indirect, which include wind, hydropower, and biomass resources.
3. Nuclear Energy Resources which include fission burner, fission breeder, and fusion systems.
4. Geothermal Energy Resources.

The scope of this investigation is directed specifically at the use of non-fossil resources to produce hydrogen, i.e., solar, nuclear, and geothermal primary energy resources. Water is the essential "feedstock" from which hydrogen is produced via various "water-splitting" processes.

An examination of the collection of hydrogen production method options shown in Figure 3-1 illustrates that while the various primary energy resources may be clearly separated, the combination of technological options leading to the production of hydrogen does not invite simple categorization. The number of specific system design permutations which could result from the options illustrated is obviously large. Moreover, the picture is further complicated by the fact that all these options must be modified by site-specific considerations such as the form and quantity of local primary energy resources available, local environmental constraints and siting restrictions, and a range of operating and economic considerations unique to the specific operation to which the hydrogen is being supplied. These latter considerations ramify into form, purity, schedule of delivery, and product pricing.

The first problem which must be addressed is the development of a system of categorization. This will provide a basis for an evaluation of the technological and economic feasibility of the non-fossil hydrogen production systems.

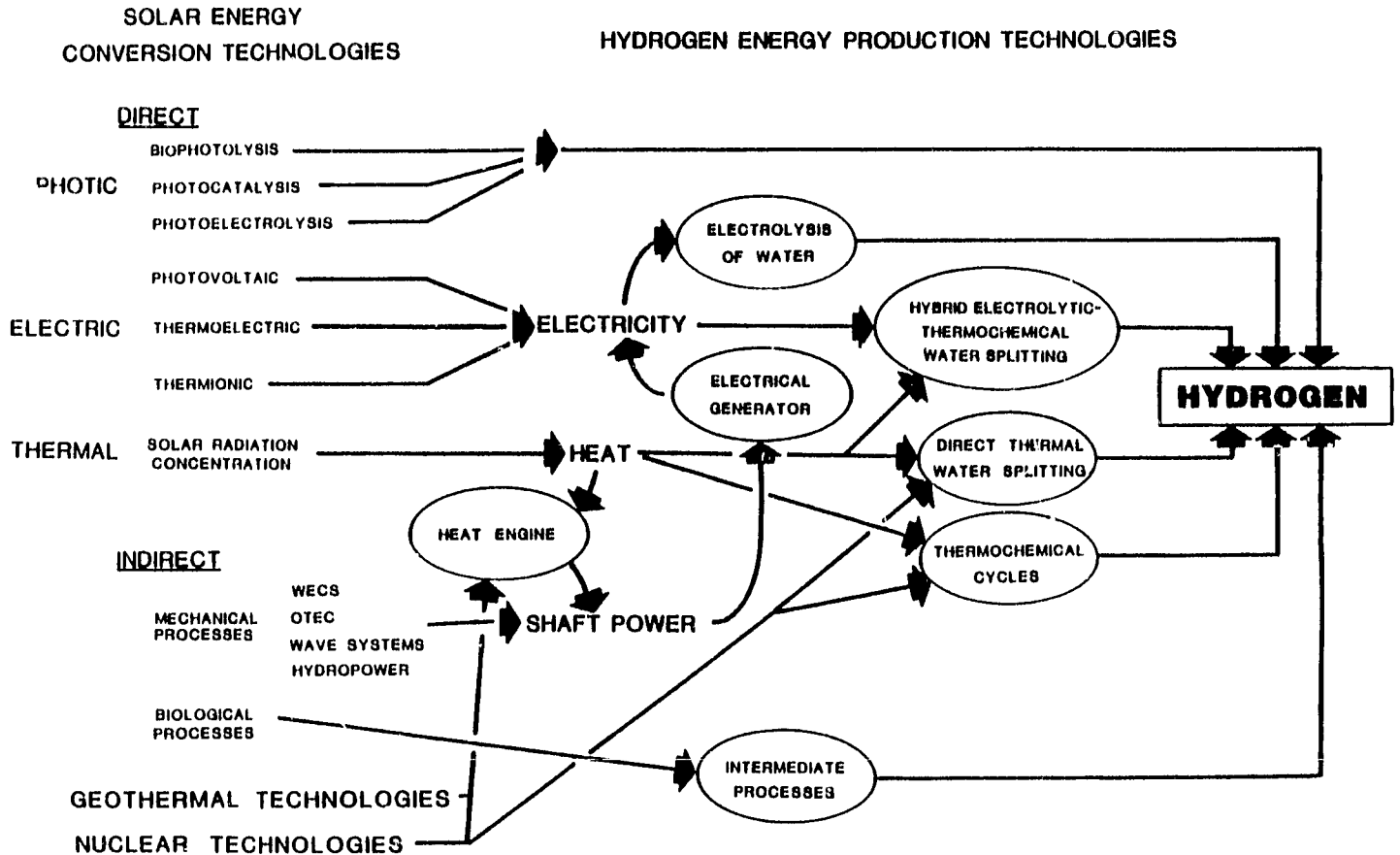


Figure 3-1. HYDROGEN PRODUCTION METHOD OPTIONS

### Hydrogen Production Process Categorization

The categorization of alternative methods of manufacture of hydrogen from non-fossil primary energy resources is illustrated in Figure 3-2. The total production process is broken down into three areas of consideration. First, the primary energy resources previously identified. Second, the technological options available to convert those primary energy resources into some form of output compatible with various technological options for producing gaseous hydrogen, generally through water-splitting processes--the third area of categorization.

### Non-Fossil Energy Conversion Technologies (ECTs)

Those technologies that interface between the non-fossil primary energy resources and the technologies used to produce hydrogen are referred to as non-fossil Energy Conversion Technologies (ECTs). These ECTs are further broken down into technologies that utilize the primary energy resources directly and those that use them in indirect modes.

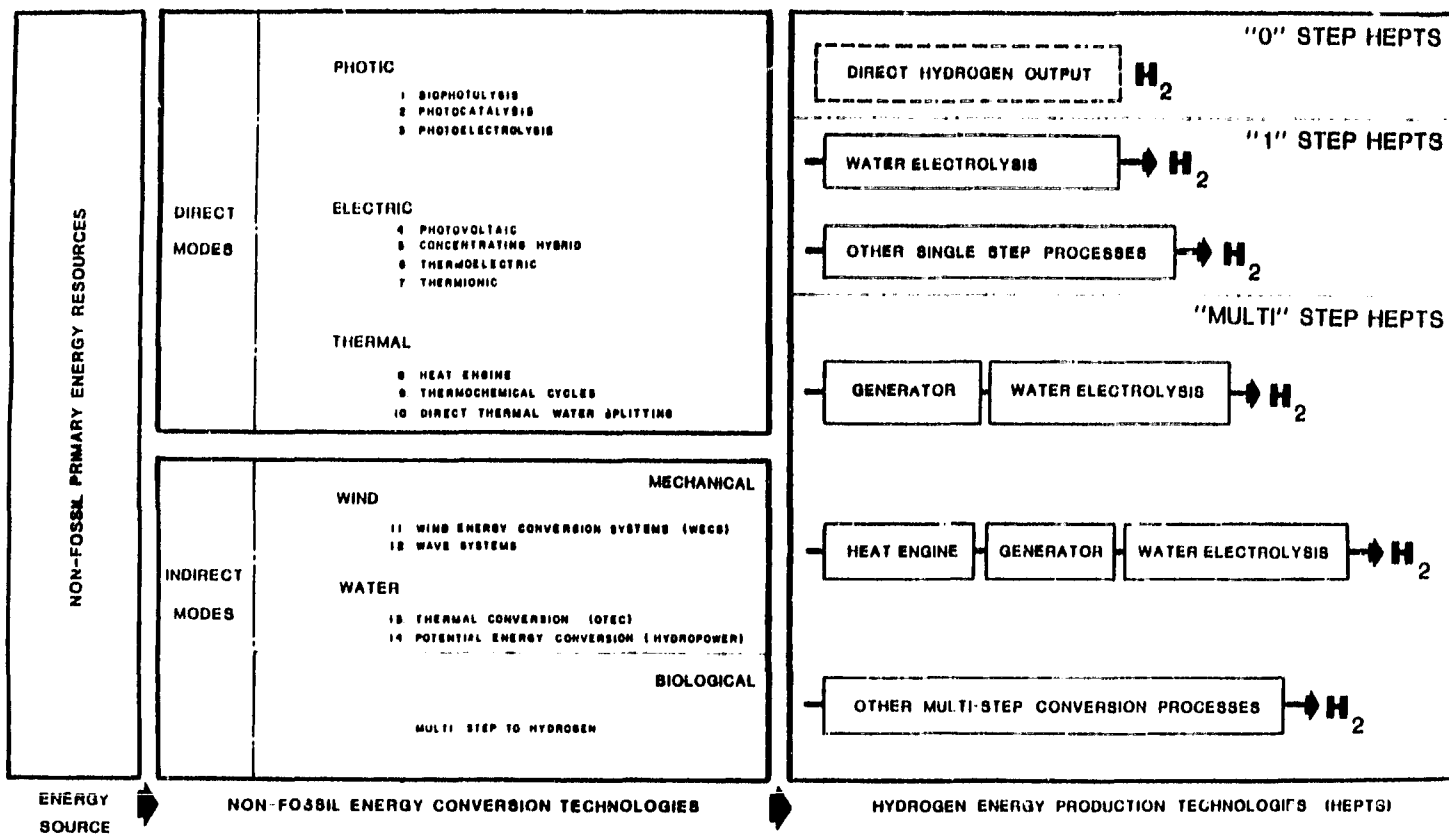


Figure 3-2. CATEGORIZATION OF ALTERNATIVE METHODS OF  
MANUFACTURE OF HYDROGEN FROM NON-FOSSIL PRIMARY  
ENERGY RESOURCES

Direct modes are further broken down into three subcategories: (1) Photonic technologies, defined here as those technologies that use solar energy (photons) directly; (2) Electric technologies, those which produce electric energy from the primary energy resource and, with the exception of photovoltaic direct-conversion systems, may be driven by any of the four primary energy resources under consideration, and (3) Thermal technologies, those that use thermal energy to provide an output compatible with the hydrogen production process input requirements and also may be driven by any of the four primary energy resource systems.

However, the use of fossil energy resources to produce electricity and thence hydrogen via water electrolysis--though technically feasible--is generally not economically competitive with direct conversion by such thermochemical processes as reformation and gasification. To illustrate this point, at the present time liquid hydrogen such as that used at KSC is produced by steam reforming natural gas.

Nuclear and geothermal primary energy systems usually represent thermal output systems and can be placed in the "direct modes" category interfacing with thermoelectric, thermionic, heat engines, thermochemical cycles, direct thermal water splitting, and hybrids of these technologies (Figure 3-2).

Indirect Modes of primary ECTs are applicable only to solar energy in the scope of this investigation. This category is broken down into two major categories of systems, those that use mechanical means and those that use biological means for energy conversion.

### Hydrogen Production Technologies (HPTs)

Given that the primary energy resource in question has been converted to some alternative energy form, this energy form must, generally, be interfaced with Hydrogen Production Technologies (HPTs) to produce the desired hydrogen product. The categorization of these HPTs is based on the number of steps required to provide the needed interface compatibility between the ECTs and the hydrogen output required. HPTs are classified as:

1. "Zero" Step Technologies, where ECTs produce hydrogen directly and no additional production step is required. Examples of such ECTs are found principally in the Photic subclass, e.g., photocatalytic water-splitting.
2. "One" Step Technologies, where only one process or production step is required to convert the output from the ECTs to hydrogen. An example of such a category is found in the interfacing of photovoltaic systems with water electrolyzers.
3. "Multi" Step Technologies, where more than one individual process or production step is required to produce hydrogen. Indirect solar energy processes such as wind-driven generators connected to water electrolyzers are of this type, for example.

Where the output of the ECTs is shaftpower, as in the case of hydropower, wind-power and heat-engine systems, electrical generation capability is required to interface the ECTs with water electrolysis or hybrid electrolytic/thermochemical water-splitting equipment to provide hydrogen product output. In these cases, several categories of generator designs are available, e.g., conventional, DC and AC, rotating machines, and magnetohydrodynamic systems. In all cases, the desired form of the electricity is DC at the Hydrogen Production Step, with voltage-matching with the water electrolyzer type of choice.

Three currently demonstrated approaches to water electrolysis as a Hydrogen Producing Technology exist:

- Unipolar Tank Electrolyzer (Alkaline Electrolyte)
- Bipolar Filter-Press Electrolyzer (Alkaline Electrolyte)
- Bipolar Solid Polymer Electrolyte (SPE) Electrolyzer (Acid Electrolyte).

In addition, high-temperature electrolysis of water vapor offers the potential of higher efficiency and is at the research level at present.



Finally, the gaseous molecular hydrogen produced by these means must be liquefied to yield liquid hydrogen,  $LH_2$ . A "conventional" hydrogen liquefaction system with the capacity for producing the requisite amount of  $LH_2$  would rely on a mechanical refrigeration expander/heat-exchange cycle (Reference 3-2). The only known alternative to such a system is found in systems based on the magnetocaloric effect or "Magnetic Refrigerators" (Reference 3-3). This subject, insofar as hydrogen liquefier applications are concerned, only recently entered the research stage.

#### Summary

A comprehensive list of technologies which can be combined into non-fossil liquid hydrogen production systems is provided in Table 3-1. By definition, the "fossil energy resource" category drops out at this point. Note that the headings are not very detailed, e.g., "Solar Thermal Engines" range from solar ponds to focusing heliostats for energy collection with several heat-engine types available to create shaftpower (Brayton-, Rankine-, Stirling-cycle systems).

Table 3-1. SUMMARY OF CATEGORIES OF TECHNOLOGICAL OPTIONS FOR THE PRODUCTION  
OF LIQUID HYDROGEN FROM NON-FOSSIL PRIMARY ENERGY RESOURCES

1. Non-Fossil Primary Energy Resources for Evaluation
  - 1.1 Solar Energy
    - 1.1.1 Non-Concentrating
    - 1.1.2 Concentrating
  - 1.2 Nuclear Energy
    - 1.2.1 Fission Burner Reactor
    - 1.2.2 Fission Breeder Reactor
    - 1.2.3 Fusion Systems
  - 1.3 Geothermal Energy
2. Non-Fossil Primary Energy Conversion Technologies for Evaluation
  - 2.1 Direct
    - 2.1.1 Photic
      - 2.1.1.1 Biophotolysis
      - 2.1.1.2 Photocatalysis
      - 2.1.1.3 Photoelectrocatalysis
    - 2.1.2 Electric
      - 2.1.2.1 Photovoltaic
      - 2.1.2.2 Thermoelectric
      - 2.1.2.3 Thermionic
    - 2.1.3 Thermal
      - 2.1.3.1 Thermal Engines
      - 2.1.3.2 Direct Thermal Water Splitting
      - 2.1.3.3 Thermochemical Water Splitting
      - 2.1.3.4 Hybrid Electrolytic-Thermochemical Water Splitting
  - 2.2 Indirect
    - 2.2.1 Mechanical
      - 2.2.1.1 Wind Energy Conversion Systems (WECS)
      - 2.2.1.2 Ocean Thermal Energy Conversion Systems (OTEC)
      - 2.2.1.3 Wave Systems
      - 2.2.1.4 Hydropower
    - 2.2.2 Biological
3. Hydrogen Energy Production Technologies for Evaluation
  - 3.1 Electrical Generation
    - 3.1.1 DC Machines
    - 3.1.2 AC Machines
    - 3.1.3 Homopolar Machines
    - 3.1.4 Magnetohydrodynamic Machines
  - 3.2 Electrolysis Systems
    - 3.2.1 Unipolar Tank Electrolyzer
    - 3.2.2 Bipolar Filter-Press Electrolyzer
    - 3.2.3 Solid Polymer Electrolyzer
    - 3.2.4 High-Temperature Electrolyzer
4. Hydrogen Liquefaction Technologies
  - 4.1 Thermomechanical Refrigeration Heat Exchanger/Expander Technology
  - 4.2 Magnetocaloric Refrigeration Technology

### References Cited in Section 3

- 3-1. "Solar/Hydrogen Systems Assessment, Vol. 1: Solar/Hydrogen System for the 1985-2000 Time Frame; Vol. 2: Solar/Hydrogen Systems Technologies," E:F Technology, Inc., St. Johns, MI, final report prepared for JPL under Contract No. 955492, and NASA under Contract No. NAS7-100, for the U.S. Department of Energy, September 1980.
- 3-2. Newton, C.L., "Hydrogen Production, Liquefaction and Use," Cryogenic Engineering News, August 1967.
- 3-3. Barclay, J.A., "Can Magnetic Refrigerators Liquefy Hydrogen at High Efficiency?" Proceedings of the 1981 National Heat Transfer Conference, Milwaukee, WI, August 1981.

#### 4. NON-FOSSIL PRIMARY ENERGY RESOURCE AVAILABILITY AT KSC

This section provides a characterization of the solar and meteorological resources available at, or immediately adjacent to, NASA's John F. Kennedy Space Center (KSC). Certain resources are also characterized within a few hundred miles of KSC leading to consideration of off-site generation and transmission of electricity, pipelined gases, or liquefied gases. Data collected at the Florida Solar Energy Center (FSEC) to characterize insolation and wind data was a primary input since FSEC is geographically adjacent to KSC at Port Canaveral, some 5-10 miles due south of the Center. It is located at about 28.4°N. latitude.

##### Solar Energy Resource Characterization

The solar radiation resource available at KSC was characterized by analyzing the data obtained from FSEC. Calendar year 1981 was chosen as the most recent complete year available. Three independent measurements are contained in the FSEC data: (1) direct (or beam) radiation measured by a fully-tracking instrument which is shielded to preclude diffuse (scattered or reflected) radiation; (2) horizontal global radiation, which consists of the sum of direct and diffuse on a flat horizontal surface; and (3) global radiation on a south-facing tilted surface. Radiation, as will be noted, a certain variable tilt-angle schedule was utilized by the FSEC researchers.

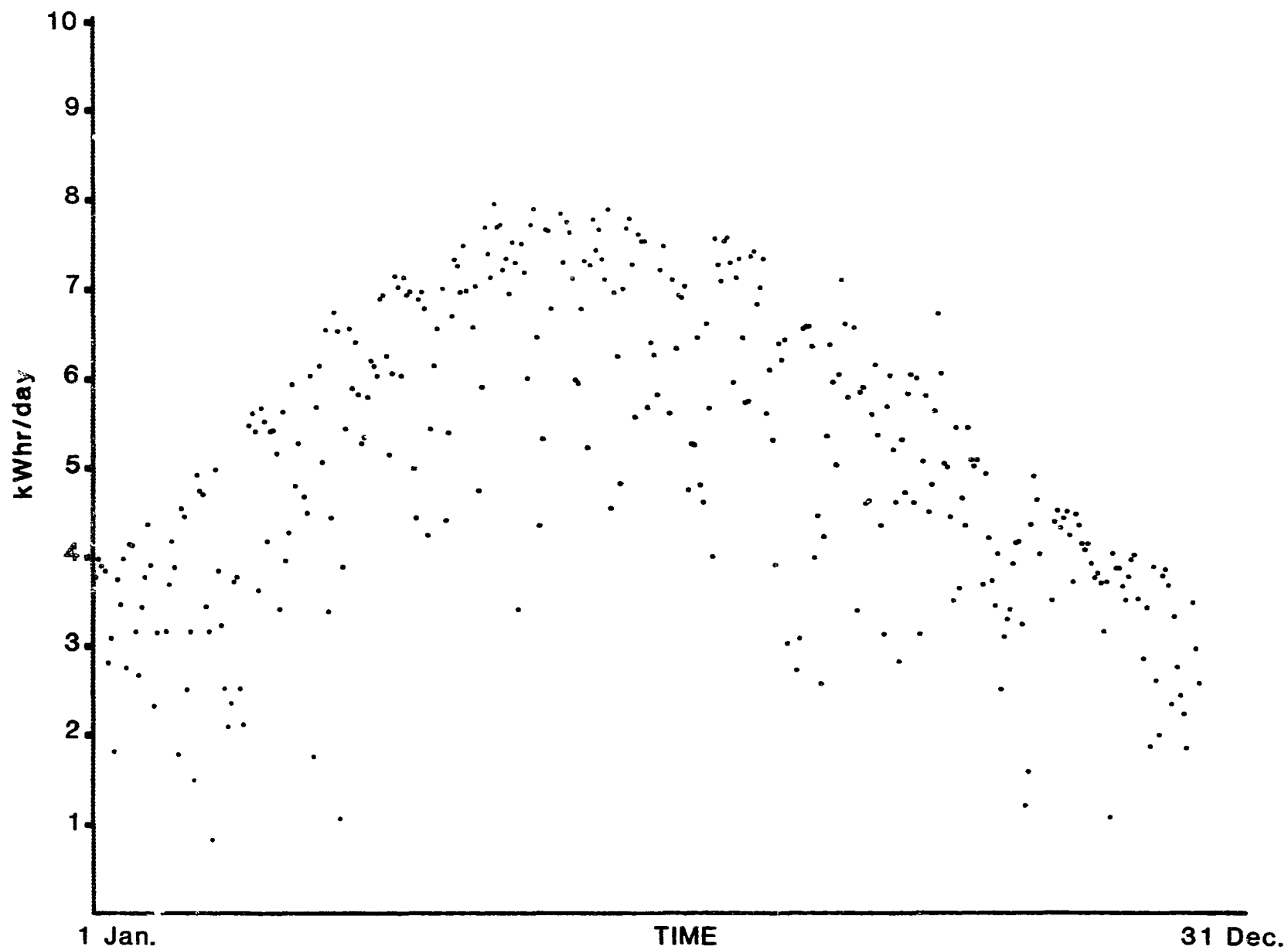
##### Global Horizontal Radiation

The observed global horizontal radiation, expressed in kWhr/m<sup>2</sup>-day, is shown in Figure 4-1. Each day in the year is represented by a dot. In the 347 days for which complete data exists, the observed energy is 1,780 kWhr/m<sup>2</sup>, which, when corrected for an entire year, is 1,872 kWhr/m<sup>2</sup>. At 30° latitude, Meinel and Meinel (Reference 4-1) note that the maximum possible annual energy yield for a horizontal plate collecting direct and scattered radiation is 2,260 kWhr/m<sup>2</sup>. Ignoring the approximate 1.5° latitude deviation from that of KSC, the observed global horizontal radiation is 83% of the maximum possible. By "maximum possible" is meant what would be observed if the sky had no clouds or dust to scatter or absorb the radiation.

There is a significant seasonal variation evident in Figure 4-1, predominantly due to the cosine effect on the incoming radiation. This seasonal variation may affect the sizing of horizontally-configured collection devices (e.g., solar ponds) using horizontal global radiation if extractable energy must remain constant throughout the year. The distribution of number of days by incident energy levels (kWhr/day) is shown in Figure 4-2. The average horizontal global energy incident throughout the year is 5.13 kWhr/m<sup>2</sup>-day. The histogram in Figure 4-2 is essentially a projection of the values shown in Figure 4-1 on the ordinate axis.

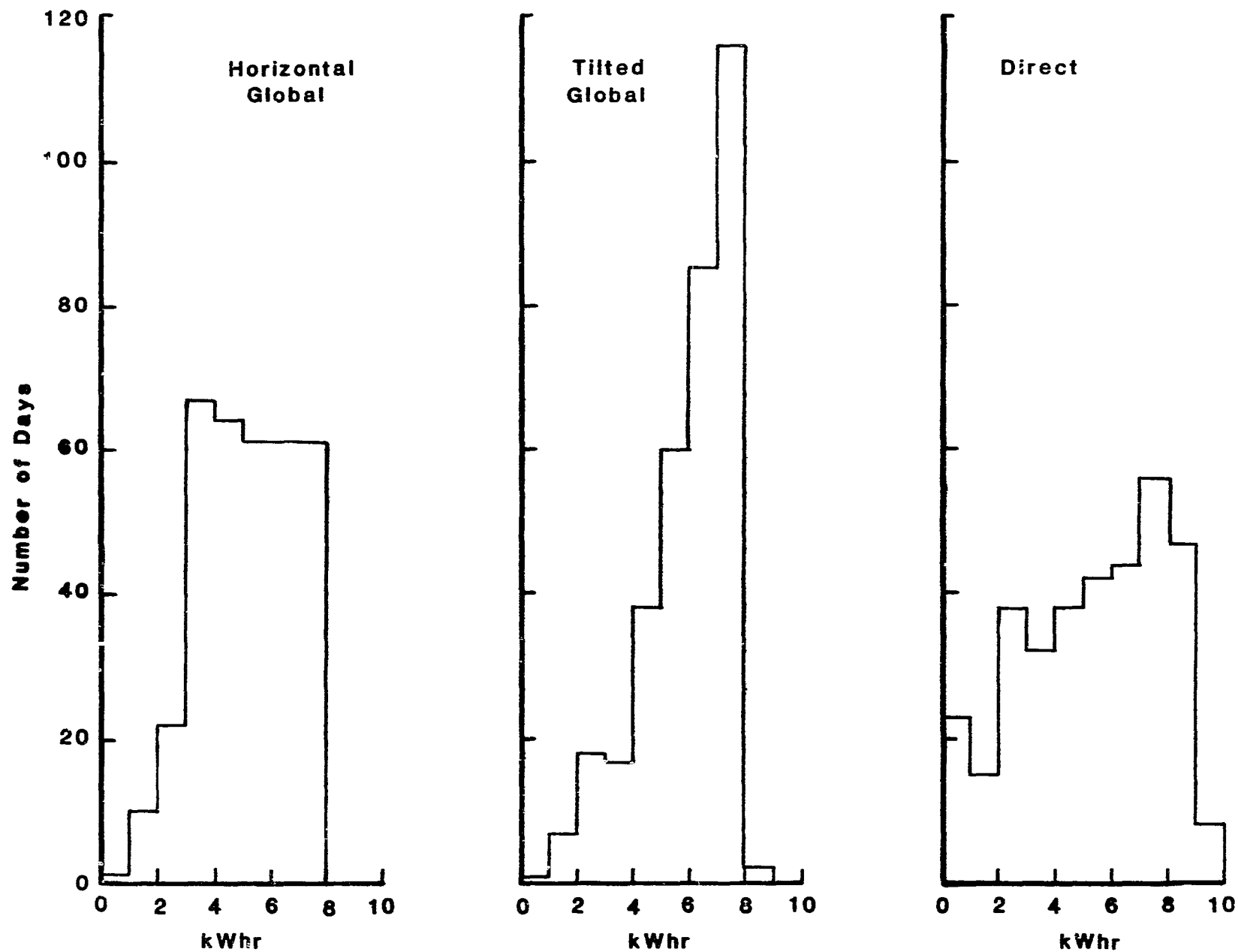
##### Global Tilted Radiation

Observed global tilted radiation expressed in kWhr/m<sup>2</sup>-day is shown in Figure 4-3. It is important to note that the tilt angle of the collector is arbitrarily changed 10 times per year such that the incident angle at solar noon does not exceed 4° from the normal. Table 4-1 shows the tilt angle and applicable dates at each tilt angle. In the 344 days for which complete data existed, 2,046 kWhr/m<sup>2</sup> were measured, corresponding to a yearly total of 2,171 kWhr/m<sup>2</sup>-year.



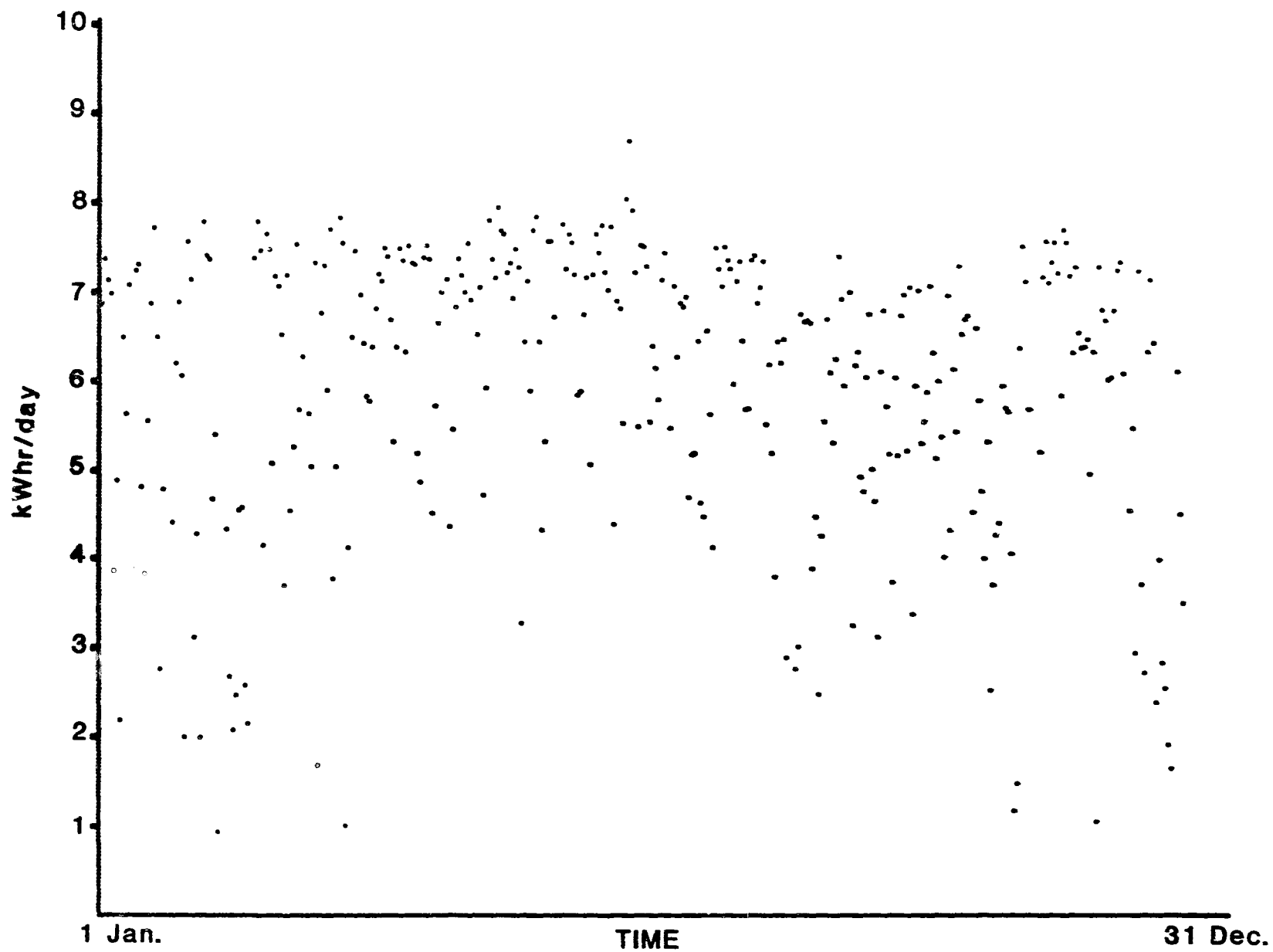
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Figure 4-1. GLOBAL HORIZONTAL RADIATION IN kWhr/DAY THROUGH YEAR 1981



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Figure 4-2. HISTOGRAM OF NUMBER OF DAYS VS. DAILY INSOLATION (1981) FOR HORIZONTAL GLOBAL, TILTED GLOBAL, AND DIRECT INSOLATION



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Figure 4-3. TILTED GLOBAL RADIATION IN kWhr/DAY THROUGH YEAR 1981

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Table 4-1. TILT ANGLE AND APPLICABLE DATES  
(Source: Reference 4-1)

<u>Tilt in Degrees</u>	<u>Date Range</u>
48	3 Nov - 9 Feb
40	10 Feb - 4 Mar
32	5 Mar - 24 Mar
24	25 Mar - 13 Apr
16	14 Apr - 7 May
8	8 May - 7 Aug
16	8 Aug - 30 Aug
24	31 Aug - 20 Sep
32	21 Sep - 10 Oct
40	11 Oct - 2 Nov

Using tables and graphs in Neville's article on collector orientation (Reference 4-2), the maximum possible radiation on this collector has been approximated as 2,610 kWhr/m<sup>2</sup>-year. The observed tilted global is thus 83% of this maximum, i.e., that which is only attainable with cloud- and dust-free air.

At an onsite experimental photovoltaic house, FSEC (Reference 4-3) measured 2,000 kWhr/m<sup>2</sup>-year incident on a collector fixed at a non-optimized 22.5° tilt angle. The optimized tilt from the 10 changes per year thus results in an approximate 8% increase in incident energy. The FSEC experimental house data covers the period from April 1981 through March 1982, while the optimized tilt data is for calendar year 1981 only--a 9-month overlap. Only a moderate seasonal variation is evident in Figure 4-3, with late-spring/early-summer being somewhat better than the winter months. The distribution of days by energy incident is shown in Figure 4-2. The average global tilted (optimal) radiation throughout the year is 5.95 kWhr/m<sup>2</sup>-day.

#### Direct Normal Radiation

Observed direct normal radiation expressed in kWhr/m<sup>2</sup>-day is shown in Figure 4-4. In the 343 days with complete data, 1,819 kWhr/m<sup>2</sup> was measured, corresponding to a yearly total of 1,936 kWhr/m<sup>2</sup>-year. At 30° latitude, Reference 4-1 indicates the maximum possible annual energy yield for direct radiation is 3,110 kWhr/m<sup>2</sup>-year. Ignoring the 1.5° latitude deviation, the observed radiation is only 62% of that possible with dust- and cloud-free air. This is in sharp contrast to the 83% of maximum experienced with global insolation as noted above. No significant seasonal variation is evident in



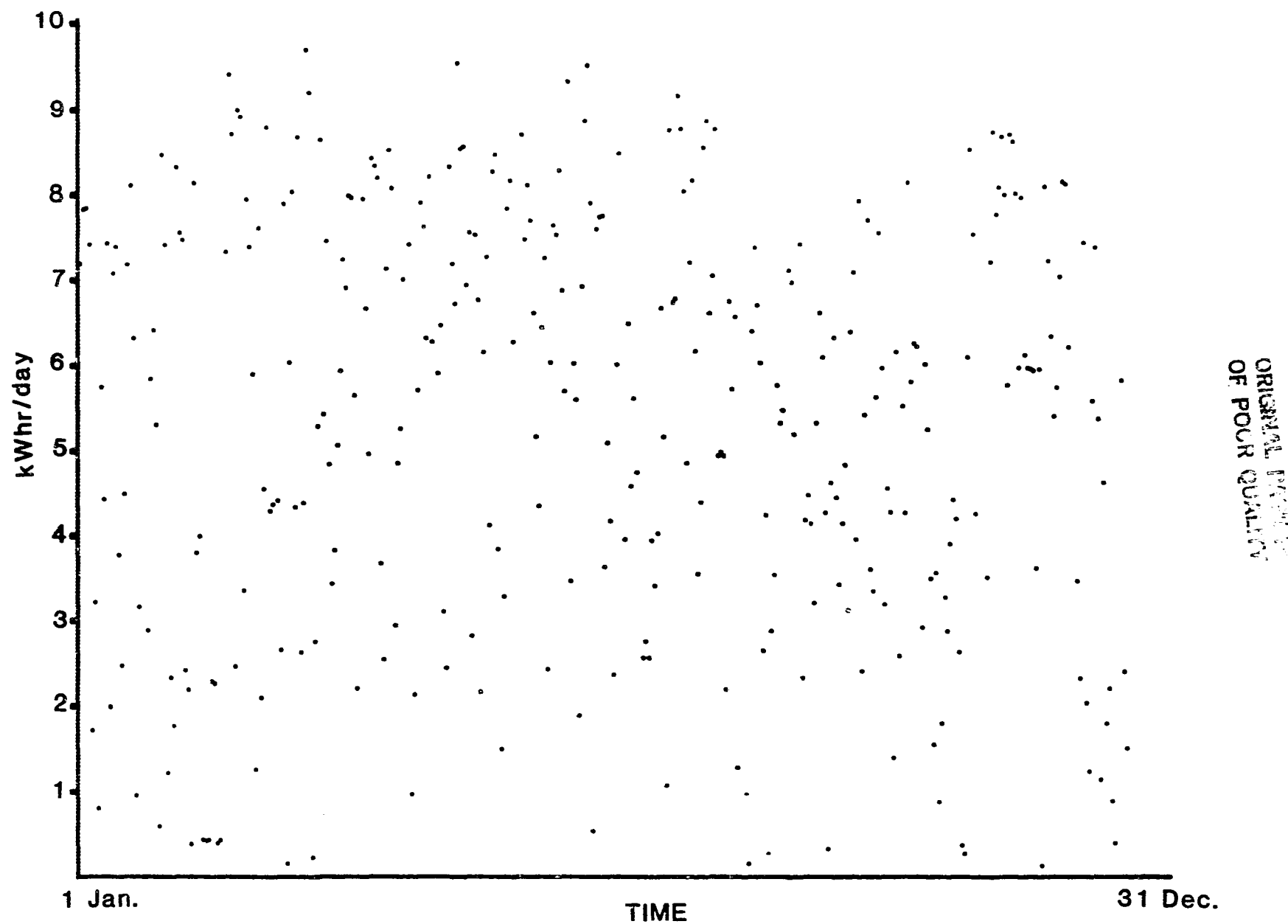


Figure 4-4. DIRECT NORMAL RADIATION IN kWhr/DAY THROUGH YEAR 1981

Figure 4-4, i.e., no radiation is year-round. The distribution of days by incident direct energy is shown in Figure 4-2 (right-hand histogram). The average direct normal radiation throughout the year is 5.30 kWhr/m<sup>2</sup>-day, or about 65% to 75% of that available in the U.S. Southwest desert (Reference 4-4). Implications of this to system sizing are discussed later.

#### Usable Solar Resource at KSC

Table 4-2 reviews the data presented thus far. The highly diffuse nature of the insolation is evident in that the horizontal global radiation is almost equal to the direct normal, and in that the global tilted radiation exceeds the direct normal. The radiation by day scatterplots for tilted and horizontal global radiations tends to clump near the upper envelope boundary. The scatterplot for direct radiation has no such clumping. A significant seasonal variation is only apparent in the horizontal global data.

Table 4-2. SUMMARY OF INSOLATION OBSERVED BY FSEC IN 1981

	<u>Horizontal Global</u>	<u>Tilted Global</u>	<u>Direct Normal</u>
Yearly Radiation (kWhr/m <sup>2</sup> )	1,872	2,171	1,936
Daily Average (kWhr/m <sup>2</sup> -day)	5.13	5.95	5.30
Percent of Maximum Possible	83	83	62

Not all the incident radiation is usable by all candidate solar energy conversion systems. For example, photovoltaic cells can operate on essentially all global tilted radiation present, while a threshold exists for other solar thermal systems (e.g., below direct radiation levels of about 200-400 w/m<sup>2</sup> some systems do not start or continue to generate useful power).

Most significantly, those solar-energy collection systems employing optical concentration can use only the direct-component of insolation, the diffuse-component not being "focusable." Thus, "flat plate" photovoltaic and thermal collectors can use global insolation (direct + diffuse); but lens, mirror focusing systems can use only the direct-component.

In this section, we examine the direct and global tilted solar radiation above a specified threshold to determine the annual usable energy and the number of days per year that usable solar energy is available. The daily patterns for those days in 1981 that did not yield continuous usable power during the course of the day are presented. This analysis should help to assess the suitability of the solar resource at KSC for various solar collection technologies.

A simple approximation for using a cutoff threshold to evaluate usable insolation has evolved from discussions with manufacturers and researchers working with medium- and high-temperature collectors (References 4-5 and 4-6). For each day, until an hour with insolation exceeding the threshold is encountered, the insolation is ignored. The first hour above threshold is then penalized 0.15 kW/m<sup>2</sup> for system warmup, and the remaining insolation is counted as "collected." Successive hours above the threshold are counted with no penalty. The first hour with insolation below the threshold, once several hours above the threshold have passed, is treated as an "idle" hour. If the next hour is above the threshold, counting is resumed. On the other hand, if the next hour is also below the threshold, the next subsequent hour above the threshold is penalized 0.15 kW/m<sup>2</sup> and the cycle is restarted.

The results from this simple "threshold" model are presented in Table 4-3 for cutoff values of 0, 200 W/m<sup>2</sup>, 300 W/m<sup>2</sup>, 400 W/m<sup>2</sup>, and 500 W/m<sup>2</sup>. The percentages shown refer to the value, with that cutoff, to total observed insolation for that collector, i.e., fully-tracking direct or flat plate global. Note the slow fall-off of usable energy as the threshold is raised. This suggests that on the days of minimal direct radiation evident in Figure 4-5, the radiation is present in small blocks of hours representing usable insolation surrounded by blocks of non-usable insolation.

Table 4-3. EFFECT OF CUTOFF THRESHOLD MODEL ON USABLE INSOLATION

Cutoff Value	Direct Usable (kWhr/m <sup>2</sup> -day)	% of Zero Cutoff Case	Global Tilted Usable (kWhr/m <sup>2</sup> -year)	% of Zero Cutoff Case
0	1,936	100.0	2,171	100.0
200 W/m <sup>2</sup>	1,793	92.6	2,012	92.7
300 W/m <sup>2</sup>	1,713	88.5	1,925	88.7
400 W/m <sup>2</sup>	1,605	82.9	1,798	82.8
500 W/m <sup>2</sup>	1,450	74.9	1,647	75.9

This observation prompted a study of the daily insolation patterns present in the 1981 FSEC data. The cutoff level of 300 W/m<sup>2</sup> used in this analysis was suggested by direct contacts with representatives of the collector industry (References 4-5 and 4-6).

The hours from 6 a.m. through 8 p.m. were examined for insolation level. If the level was less than or equal to the cutoff, a "0" (zero) was entered for that hour. An hour with insolation greater than the cutoff was characterized by a "1" (one). Thus, a day where the insolation starting at 10 a.m. was greater than cutoff for 8 hours and then below cutoff for the remainder of the day would be characterized by the representation "0000111111100," etc. This hypothetical day would be called an "8,8," i.e., 8 hours of useful insolation with all 8 hours contiguous. A day of "00110001111000" would then be called a "6,4" by the same logic, i.e., 6 hours useful with at most 4 hours contiguous.

The available direct insolation characterized in this fashion for the 1981 FSEC data is shown in Figure 4-5. The data on the diagonal of the array where the hours are all contiguous are circled. For example, to find the 8,8 days, one enters the array on the ordinate ("Total Hours" axis) at 8 and looks for the cell corresponding to at most 8 hours consecutive--finding 24 such days. Notice that the lower right triangle of the array corresponds to patterns which cannot occur since there cannot be more contiguous hours than total hours of useful insolation.

It is the off-diagonal elements of this day characterizing array which may cause problems in solar thermal collectors, i.e., days where the insolation fluctuates between above and below cutoff level. There are 55 such days in the 344 days of direct radiation studies (16%). For example, to find

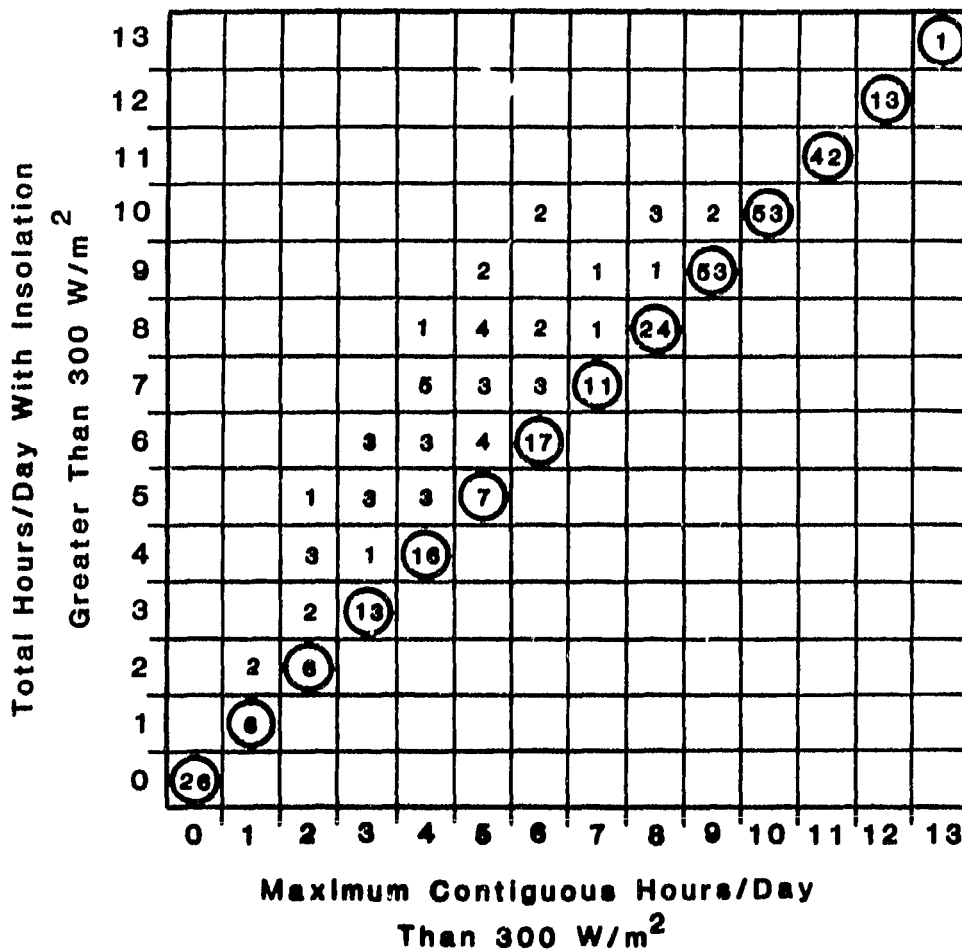


Figure 4-5. DIRECT INSOLATION -- CHARACTERIZATION OF 343 DAYS IN 1981 BY MAXIMUM TOTAL NUMBER AND MAXIMUM CONSECUTIVE NUMBER OF HOURS ABOVE 300 W/m<sup>2</sup> THRESHOLD

the number of 6,4 days, the table is entered on the maximum hours axis at 6 and the cell corresponding to at most 4 hours consecutive. These days are displayed in full in Table 4-4 in descending order of number of contiguous hours of insolation above the threshold. The characterization on the right side of the table represents how the simple model characterized these days. An "OK" means at most one off-hour between periods of adequate insolation; a "RESTART" means at least two hours between periods of adequate insolation, where the startup penalty of 150 W/m<sup>2</sup> is reapplied.

The 3 days in the above example with 6,4 patterns can be quickly located using Table 4-4. Three unique patterns are present: the first and second being quite similar but offset an hour, i.e., "00011110011000" and "00001111001100," with both containing a 2-hour gap between periods of insolation above the 300 W/m<sup>2</sup> threshold. The third pattern has a 4-hour gap, represented as "00110000111100."

A further category called "MARGINAL" was applied to a few days with highly intermittent patterns and few total hours of adequate insolation. Five such days--with 15 total hours of insolation above the threshold--are noted in Table 4-4. To be perhaps overly restrictive, one might term a day "useful" only if there were 4 or more hours above the threshold with at least 3 such hours contiguous. On this basis, direct insolation supplied useful collectible insolation on 83% of the days studied in 1981.

Table 4-4. HOURLY PATTERNS FOR 55 DAYS WITH NON-CONTINUOUS DIRECT RADIATION  
ABOVE 300 W/m<sup>2</sup> FROM 6 a.m. to 8 p.m.

Number of Days	Total Hours	Max. Hours in a Row	Pattern	Status
2	10	9	0101111111100	OK
2	10	8	01111111101100	OK
1	10	8	01101111111100	OK
1	9	8	01111111101000	OK
1	9	7	00111111101100	OK
1	8	7	01011111110000	OK
1	10	6	01111011111100	OK
1	10	6	01111110111100	OK
1	8	6	00111111011000	OK
1	8	6	01111110110000	OK
1	7	6	00010111111000	OK
1	7	6	01011111100000	OK
1	7	6	00100011111100	RESTART 3 HRS
1	9	5	00111110111100	OK
1	9	5	01111001111100	RESTART 2 HRS
3	8	5	00111110011100	RESTART 2 HRS
1	8	5	00111110111000	OK
1	7	5	00011001111100	RESTART 2 HRS
1	7	5	01111100001100	RESTART 4 HRS
1	7	5	00110011111000	RESTART 2 HRS
1	6	5	00111110100000	OK
1	6	5	00100111110000	RESTART 2 HRS
1	6	5	00010011111000	RESTART 2 HRS
1	6	5	01111100001000	RESTART 4 HRS
1	8	4	00011110111100	OK
1	7	4	00111100110100	RESTART 2 HRS
1	7	4	00011101111000	OK
1	7	4	00111001111000	RESTART 2 HRS
1	7	4	00110111101000	OK
1	7	4	00111101110000	OK
1	6	4	00011110011000	RESTART 2 HRS
1	6	4	00001111001100	RESTART 2 HRS
1	6	4	00110000111100	RESTART 4 HRS
1	5	4	00001001111000	RESTART 2 HRS
1	5	4	00000101111000	OK
1	5	4	00111100100000	RESTART 2 HRS
1	6	3	00111001110000	RESTART 2 HRS
1	6	3	01110111000000	OK
1	6	3	00111000111000	RESTART 3 HRS
1	5	3	00000110111100	OK
1	5	3	00001100011100	RESTART 3 HRS
1	5	3	01100011100000	RESTART 3 HRS
1	4	3	01110001000000	RESTART 3 HRS
1	5	2	00001011011000	OK
1	4	2	00011000000110	MARGINAL
1	4	2	00011011000000	OK
1	4	2	00100100011000	MARGINAL
1	3	2	00011001000000	MARGINAL
1	3	2	00000001011000	OK
1	2	1	00001000010000	MARGINAL
1	2	1	00000100100000	MARGINAL

Global tilted insolation data are presented in an analogous way in Figure 4-6 and Table 4-5. To continue the example, 67 days have 8,8 patterns and no days were observed with a 6,4 pattern. There are only 19 days in the off-diagonal part of the array, i.e., for 94.5% of the days, all useful hours above  $300 \text{ W/m}^2$  were contiguous hours. Using the same restrictive characterization for useful days (i.e., a day has to be 4,3 or better) reveals that the global tilted insolation can be usefully collected on 94% of the days studied in 1981.

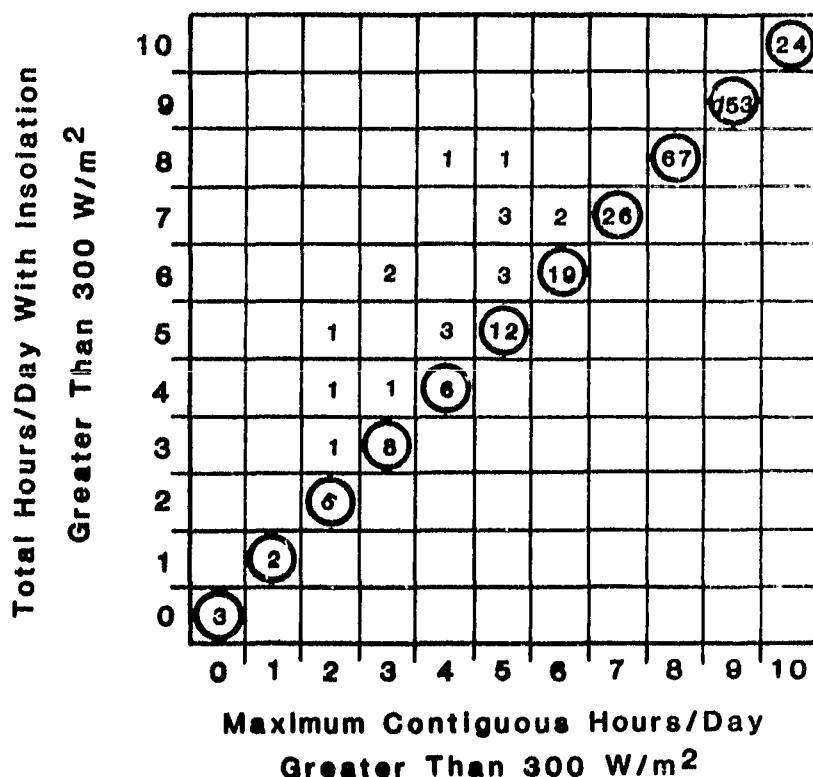


Figure 4-6. TILTED GLOBAL INSOLATION -- CHARACTERIZATION OF 344 DAYS IN 1981 BY MAXIMUM TOTAL NUMBER AND MAXIMUM CONSECUTIVE NUMBER OF HOURS ABOVE  $300 \text{ W/m}^2$  THRESHOLD

Table 4-5. HOURLY PATTERNS FOR 19 DAYS WITH NON-CONTINUOUS GLOBAL TILTED RADIATION > 300 W/m<sup>2</sup> FROM 6 a.m. TO 8 p.m.

Number of Days	Total Hours	Max. Hours in a Row	Pattern	Status
2	7	6	00111111010000	OK
1	8	5	00111110111000	OK
1	7	5	00011111011000	OK
1	7	5	00011011111000	OK
1	7	5	00111110011000	RESTART 2 HRS
1	6	5	00001111101000	OK
1	6	5	00011111010000	OK
1	6	5	00010111110000	OK
1	8	4	00111101111000	OK
1	5	4	00111100000100	RESTART 5 HRS
1	5	4	00001111010000	OK
1	5	4	00011110010000	RESTART 2 HRS
1	6	3	00111011100000	OK
1	6	3	00011100111000	RESTART 2 HRS
1	4	3	00111000001000	RESTART 5 HRS
1	5	2	00011011001000	RESTART 2 HRS
1	4	2	00000110110000	OK
1	3	2	00011000010000	MARGINAL

#### Summary of the KSC Solar Insolation Resource

Table 4-6 contains the major results of the 1981 Cape Canaveral data obtained from FSEC. Direct normal insolation is present, although in reduced amounts from those locations in the U.S. southwest desert regions which have 2,500-2,700 kWhr/m<sup>2</sup>-year of direct insolation. The implications of this for concentrating tracking collectors is that installations would have to be upsized 35% to 50% to convert the same annual amount of energy as equivalent collectors based in the desert would.

Table 4-6. SUMMARY CHARACTERIZATION OF 1981 CAPE CANAVERAL SOLAR RADIATION

	<u>Direct Normal</u>	<u>Tilted Global</u>	<u>Horizontal Global</u>
Maximum Possible With Clear Sky (kWhr/m <sup>2</sup> -year)	3,110	2,610	2,260
Observed (kWhr/m <sup>2</sup> -year) (% of Maximum)	1,936 (62)	2,171 (83)	1,872 (83)
Observed in Hours Above 300 W/m <sup>2</sup> (kWhr/m <sup>2</sup> -year) (% of Maximum)	1,713 (55)	1,925 (74)	n.a. (--)

Designs based on the use of tilted global insolation appear to offer promise since 83% of the maximum possible (clear sky) radiation was actually present in the 1981 data. The possibility exists that tracking flat plate

collectors would yield still additional collectible insolation; however, this remains to be investigated in the cost/benefit sense. Should 83% of the maximum 3,110 kWhr/m<sup>2</sup>-year actually be collectible, the global tracking yield would be 2,580 kWhr/m<sup>2</sup>-year--comparable to the direct radiation observed in the southwest desert.

Collectors using horizontal global radiation also offer some promise since the 1981 data indicate that 83% of the possible (clear sky) radiation is collectible. Radiation patterns for this resource were not analyzed, since, e.g., solar ponds are not critically affected by hourly variations being more sensitive to monthly variations. The most intense resource is the global tilted (with a tracking option perhaps offering still greater enhancement). The direct normal radiation is usable, but cost considerations of upsizing existing tested and proposed facilities may reduce the practical utility of this resource in competition with alternative approaches.

#### Wind Availability at KSC

The wind resource available at KSC was characterized by analyzing the data obtained from FSEC (see Appendix). Calendar year 1981 was chosen as the most recent complete year available. Data were present for wind speed in 8,597 of the 8,760 possible hours. The remaining 163 hours have missing data. Wind speed was measured at a height above ground level of 10 meters.

A histogram of the 8,597 observations is shown in Figure 4-7. The same data are given in a slightly different form in Figure 4-8, which shows the percent of time that the wind equals or is greater than a given speed. Figure 4-9 shows the variation of daily root mean cube wind speed each day for 1981. The root mean cube wind speed is the speed at which the wind would remain constant throughout the period considered and produce the same energy as that observed with different speeds. Applying the one-seventh power law to take the mean wind speed to a height of 50 meters results in an annual power figure of 0.121 MWhr/m<sup>2</sup>-year (Reference 4-8). As is shown, no clear seasonal variation is evident except for a gentle mid-year lull in relative wind speed.

It is generally accepted that a wind power density of less than 2.0 mWhr/m<sup>2</sup>-year is uneconomical to exploit with available-technology wind-energy conversion systems (Reference 4-7). The wind resource at KSC is sufficiently below this figure to effectively rule out wind utilization for hydrogen production for a reasonably near-term application, viz., 1987-1992.

Maps showing the availability of adequate wind resources have been prepared from existing wind speed measurements (Reference 4-7). These characterize the resource as NOT USEFUL (<2 MWhr/m<sup>2</sup>-year), LOW (2-4 MWhr/m<sup>2</sup>-year), MODERATE (4-7 MWhr/m<sup>2</sup>-year), and HIGH (>7 MWhr/m<sup>2</sup>-year). Figures 4-10 and 4-11 show the geographic distribution of wind energy using these categories at surface level and at 50 meters. The only nearby (relatively) location of favorable wind energy is offshore, a minimum of 100 miles to the northeast. Economics of construction and transmittal of an energy conversion system at sea and an energy delivery means to KSC tend to strongly rule out use of these winds.



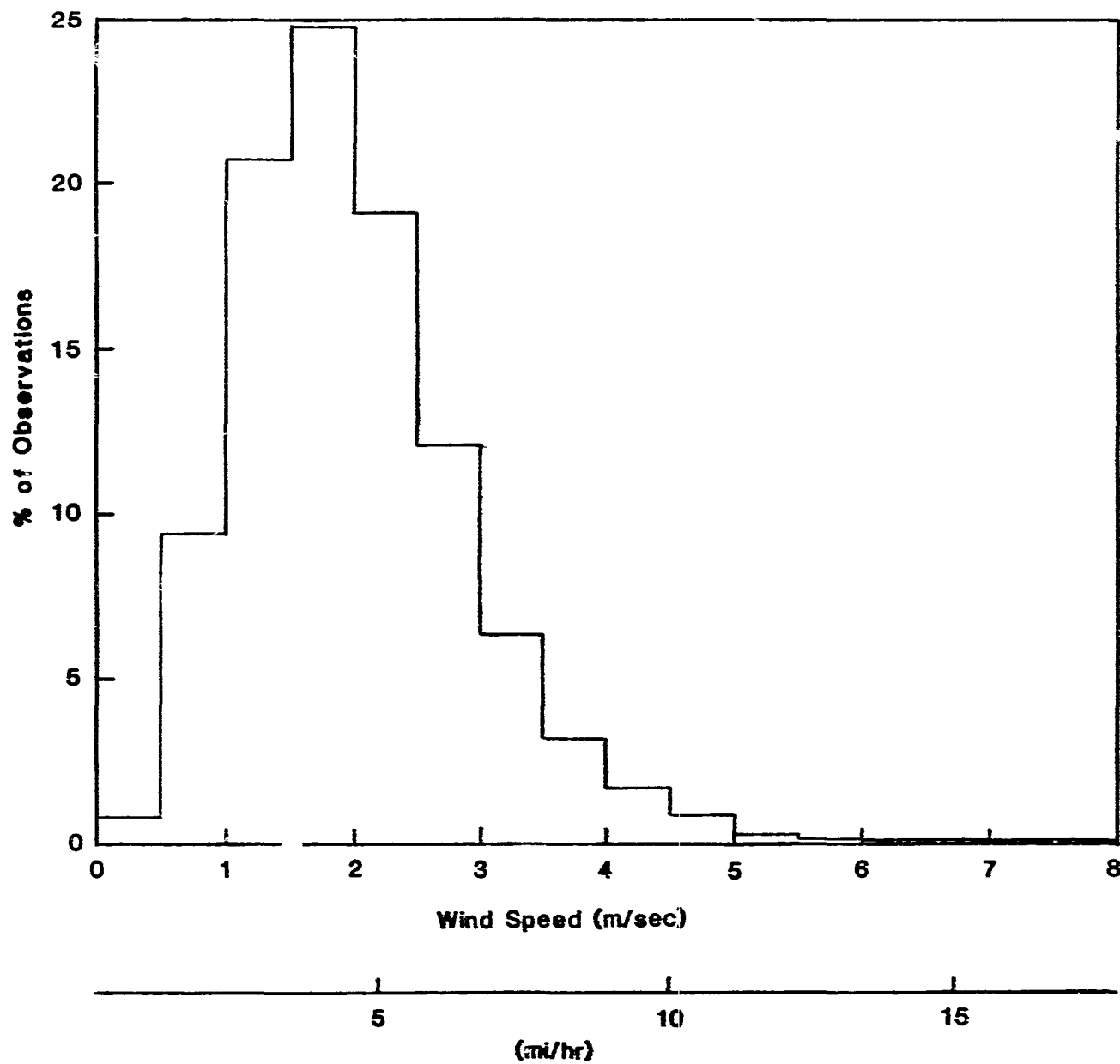
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Figure 4-7. FSEC OBSERVED WIND SPEED, 1981

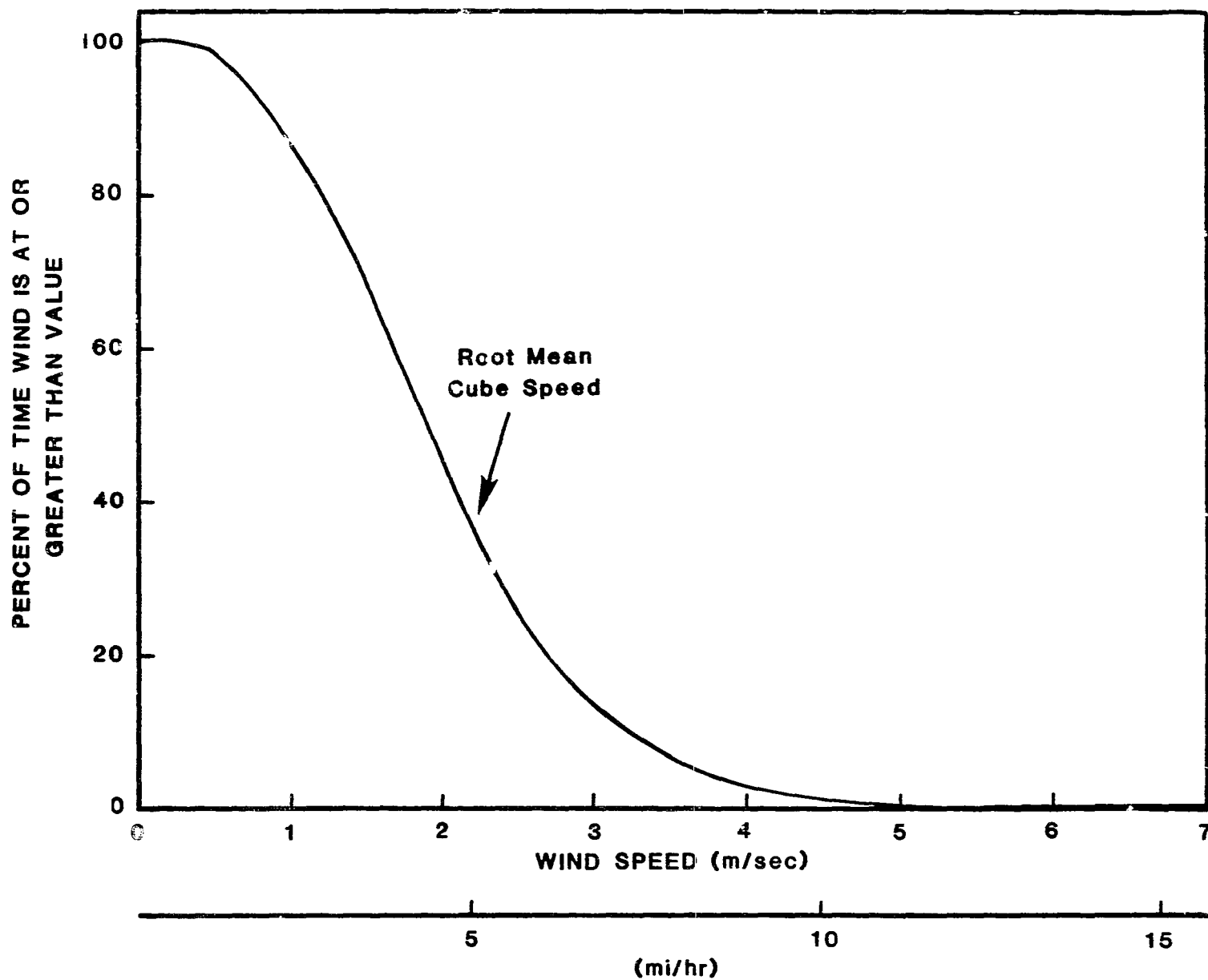


Figure 4-8. PERCENT OF TIME THAT WIND EQUALS OR IS GREATER THAN A GIVEN SPEED

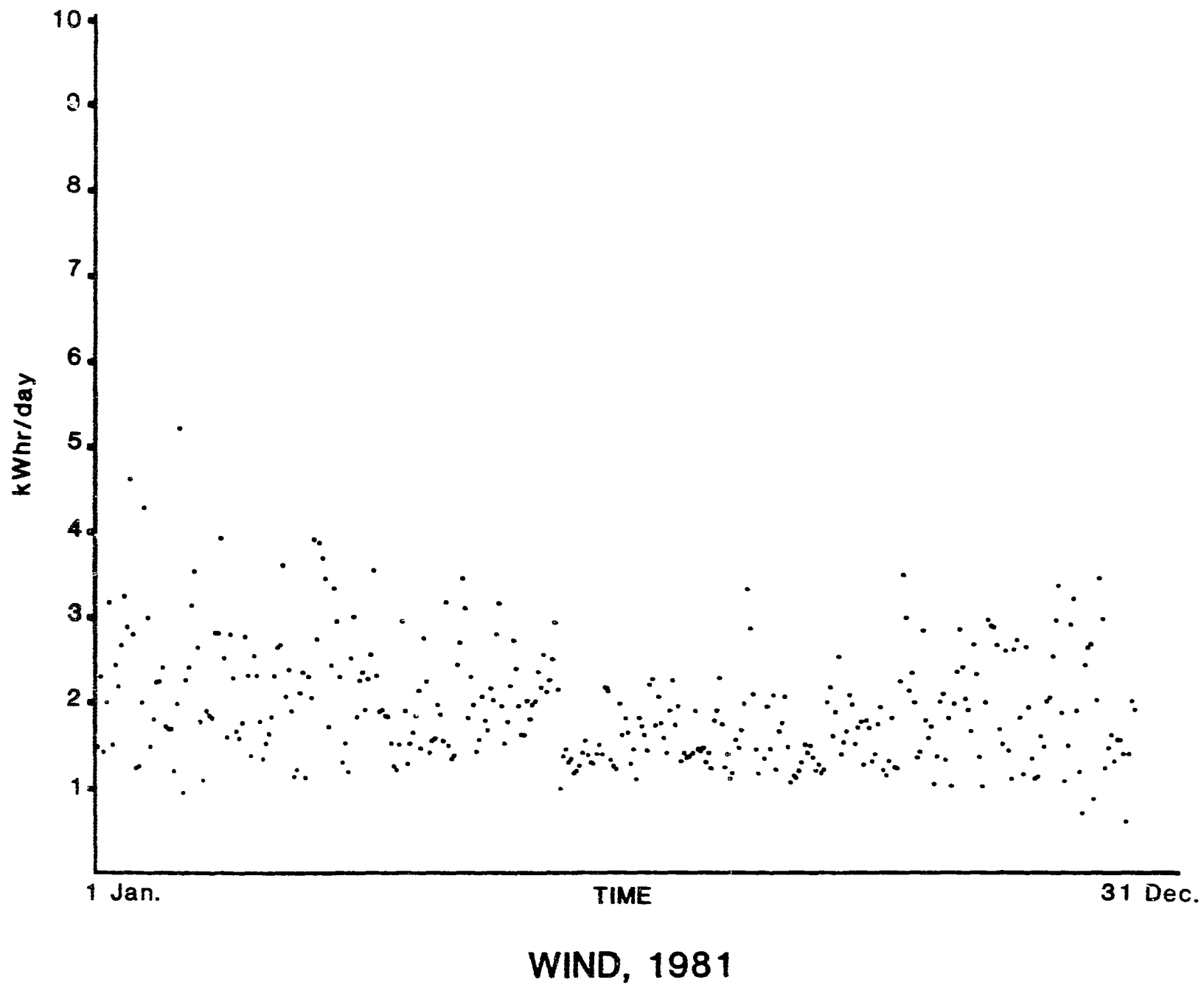
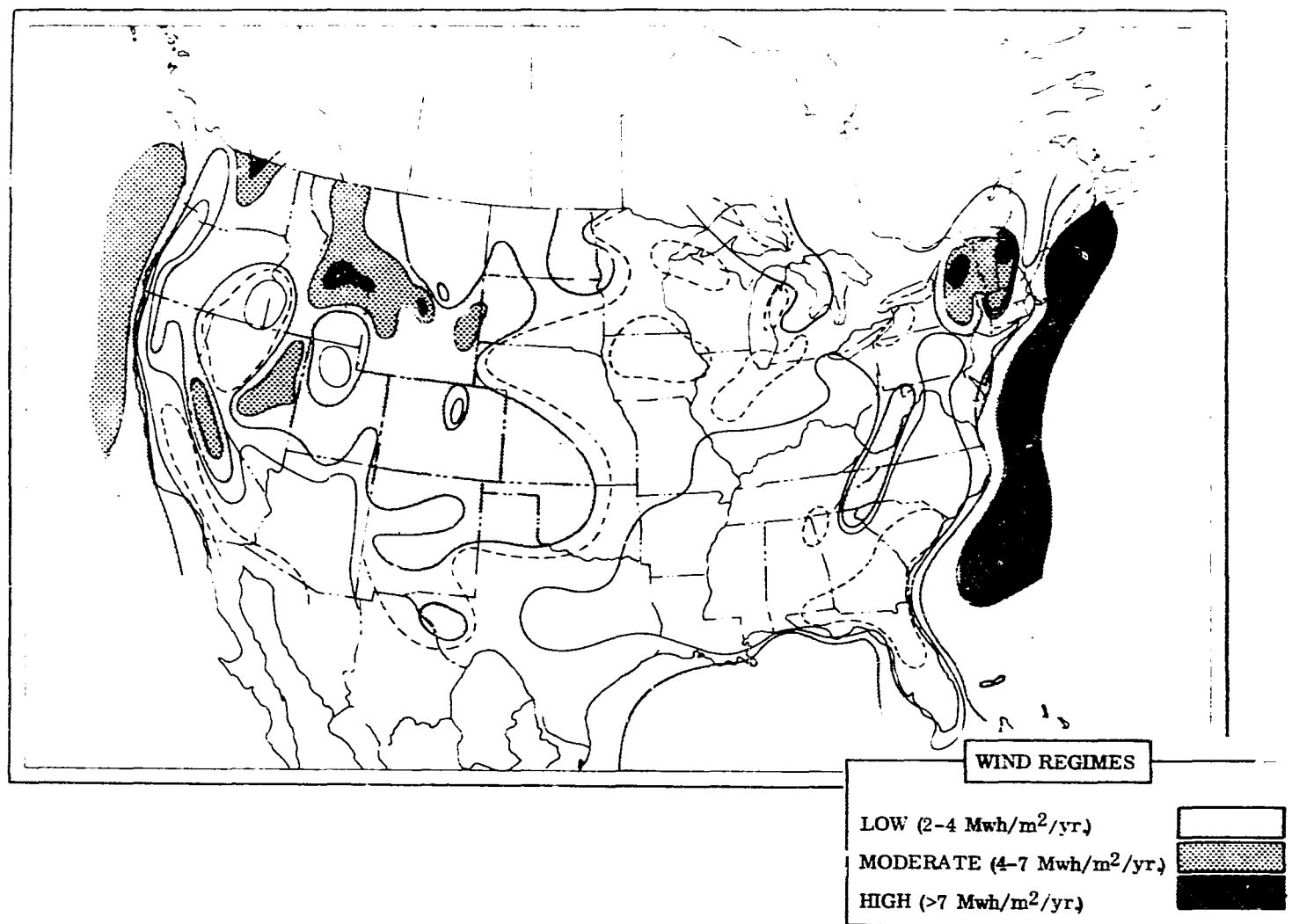
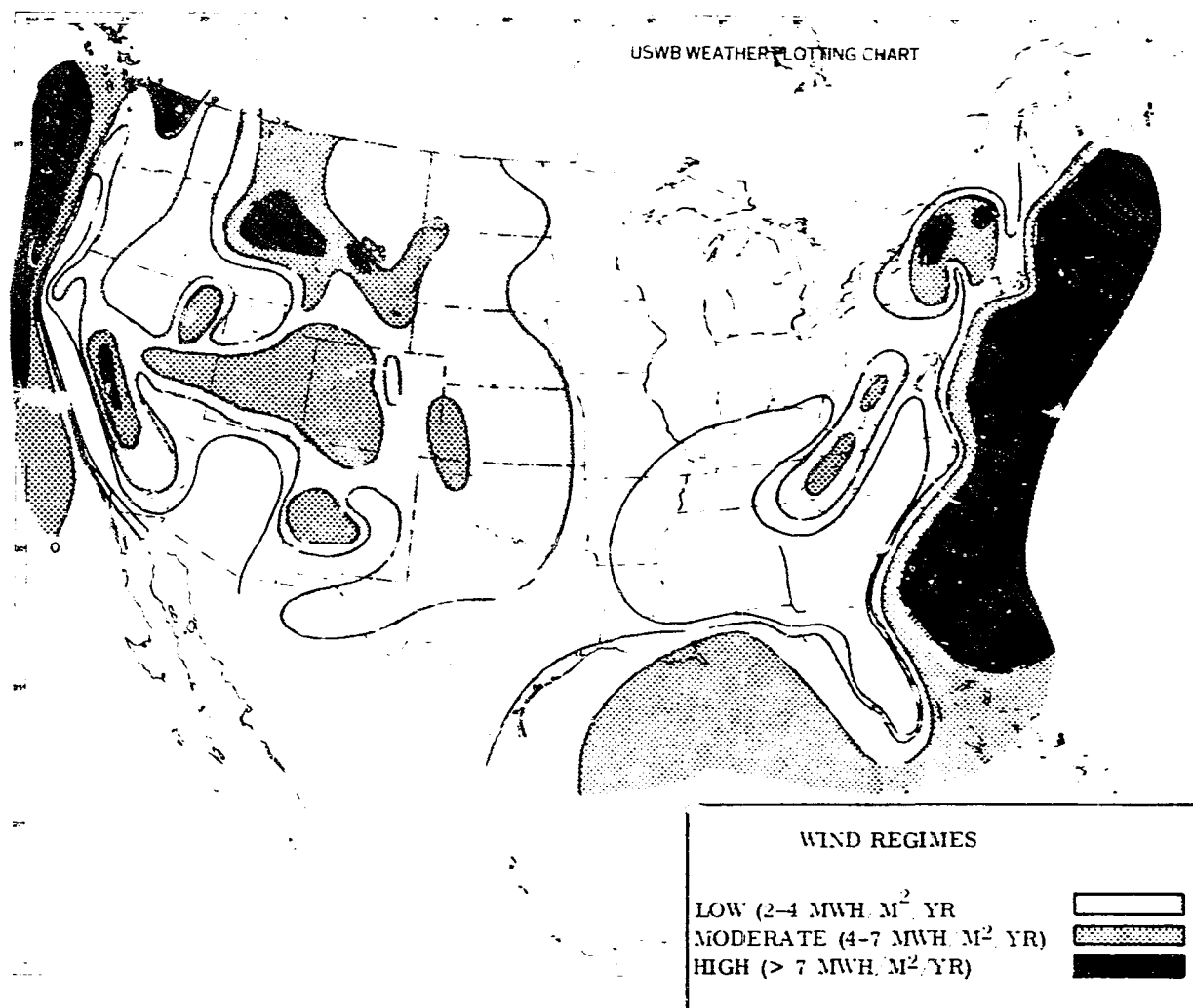


Figure 4-9. ROOT MEAN CUBE SPEED FOR WIND



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Figure 4-10. HIGH, MODERATE, AND LOW ENERGY REGIME DEPICTED AT SURFACE LEVEL (MWhr/m<sup>2</sup>-year) (Reference 4-7)



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Figure 4-11. HIGH, MODERATE, AND LOW ENERGY REGIME DEPICTED AT  
50 METERS (MWhr/m<sup>2</sup>-year) (Reference 4-7)

## OTEC Resource

The principal source of data in this category is work done for a masters thesis by Leslie Diane Sivak at the Florida Institute of Technology in 1978 (Reference 4-9). The geographical focus of this Florida-oriented work is to the east and south of the Florida peninsula, generally within the Gulf Stream system. It is pointed out that this system "is noted for the great temporal and spatial variability of its thermal and current regimes" (Reference 4-9). The variability of the current is indicated in Figure 4-12. As usually conceived, ocean thermal energy conversion (OTEC) relies on a temperature difference between water near the surface and water several hundred meters deep. A map containing the 10-fathom (18.3 meter), 100-fathom (183 meter), and 500-fathom (915 meter) contours in the straits of Florida is shown in Figure 4-13. Note that the 100-fathom contour is some distance east of Cape Canaveral.

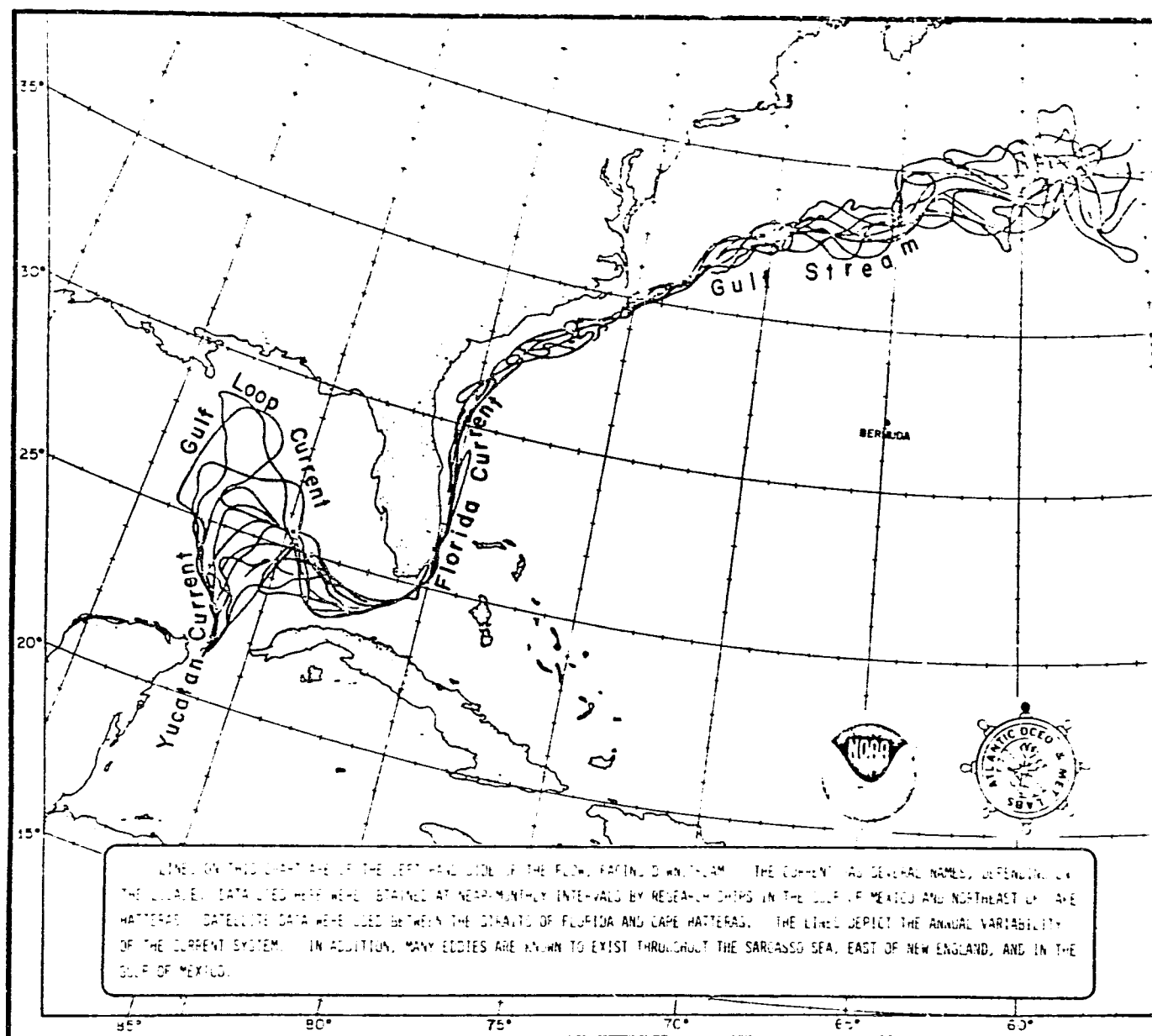
Temperature data analyzed in Reference 4-9 were taken from magnetic tapes supplied by the National Oceanographic Data Center, and contained information from the Oceanographic Station Data File, the Mechanical Bathythermograph File, and the Expendible Bathythermograph File. The Sivak study came to the following broad conclusions for the nature of the offshore OTEC resource:

"The waters within the 0-200 meter depth interval are highly responsive to changes caused by the daily heating pattern and seasonal climatological changes. Consequently, the thermal resource is not stable nor persistent for this depth interval. It is highly doubtful (at this time) that OTEC plants will be designed with warm water and cold water intakes sized to utilize the resource within the 0-200 meter depth interval.

"Conditions are more favorable for deployment of OTEC plants within the 0-400 meter depth than for the 0-200 meter depth. It appears that OTEC facilities could operate at least three months of the year (July through September) north of the Florida Straits region or from late-May to early-October if they are located within the Straits of Florida, if a 20°C thermal resource is acceptable to the OTEC planners and designers.

"The 0-500 meter depth interval appears to have rather good conditions for OTEC deployment with a 20°C thermal resource present at some location south of 25°N latitude within the study area for about eight months of the year. During the summer, the resource reached its greatest magnitude: at 24°C  $\Delta$  T.

"For the 0-600 meter depth interval, the thermal resource appears to be the best as far as extent is concerned with 22°C  $\Delta$  T water present for approximately five months of the year. 20°C  $\Delta$  T water is present for nine months of the year. The summer resource is characterized by a 24°C temperature difference.



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Figure 4-12. VARIABILITY IN THE GULF STREAM SYSTEM

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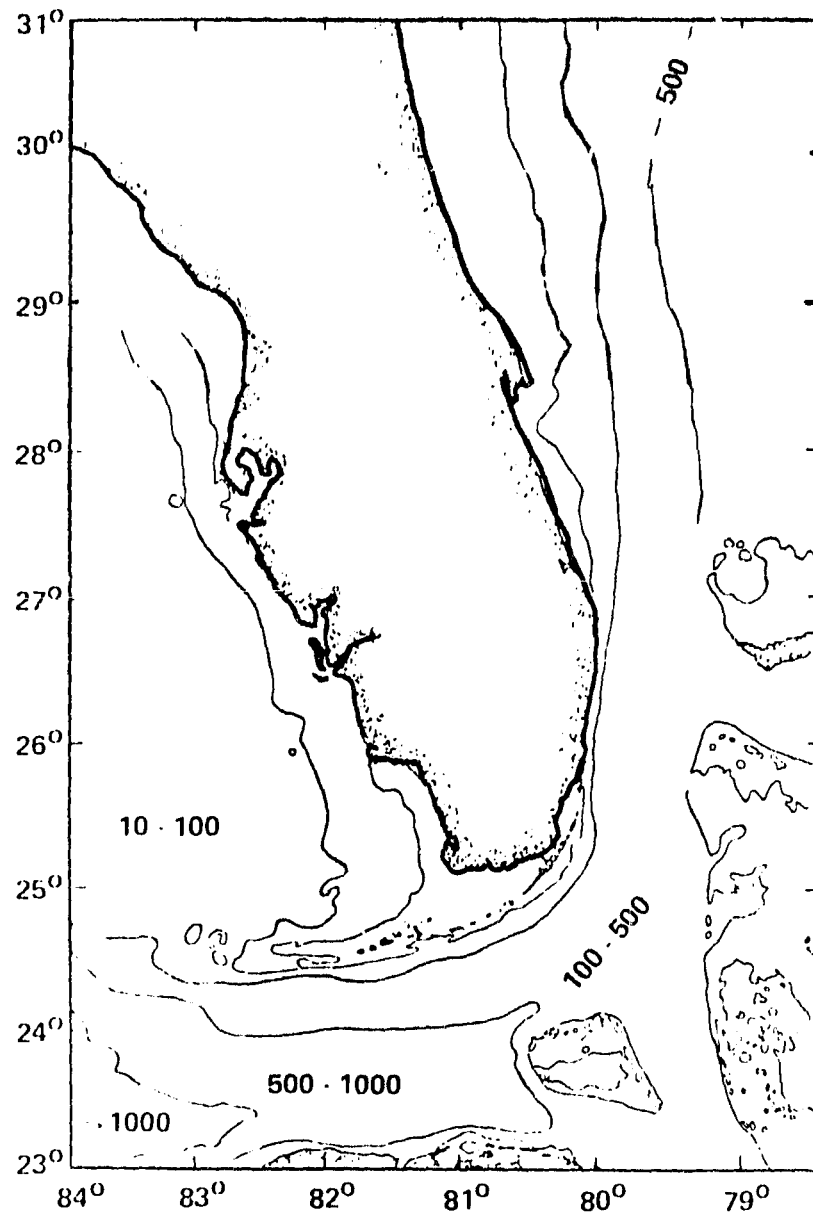


Figure 4-13. BATHYMETRIC CHART OF THE STRAITS OF FLORIDA  
IN 500-FATHOM INTERVALS, BUT ALSO SHOWING 10- AND 100-  
FATHOM CONTOURS (After Stommel, 1965)



"Few areas within this study region except for that portion south and west of 24°N and 82°W, respectively, are as deep as 800 meters. Since the Fishery Conservation Zone drawn on the maps is an approximation, it is unclear at this time how much of the thermal resource of the area is in either United States or international waters. Since few stations as deep as 800 meters were taken, the only thing that can be said about the thermal resource for the 0-800 meter depth interval is that it varies between 20°C and 24°C over most of the year."

Many illustrations appear in the study. Figures 4-14, 4-15, 4-16, and 4-17 represent a digestion of the month-by-month graphs and concluding text as to where the KSC study team believes the OTEC resource to be located. For depths of 500 meters and more, Figure 4-14 shows the locations of the surveyed regions which indicate a year-round  $\Delta T=17^{\circ}\text{C}$  OTEC resource. The same regions show this resource at greater depths as well.

The portion of the year with  $\Delta T=20^{\circ}\text{C}$  at 500 meters is shown in Figure 4-15, while the same resource at 600 meters is shown in Figure 4-16. At best, 20°C is attainable for 3/4 of the year or less. Finally, in Figure 4-17, the  $\Delta T=20^{\circ}\text{C}$  resource is found to be suggested year-round only in the region southwest of Key West. To meet KSC launch schedules, the liquid hydrogen must be manufactured year-round. Because higher efficiencies and lower costs result from higher available  $\Delta T$ , it appears that the closest location with a suggested existant resource is 50-70 miles south and southwest of Key West.

### Tides

In a review article, Merriam (Reference 4-10) points out that:

"The first thing to appreciate about tidal power is that the total resource is not very large. This is primarily because there are only a small number of possible sites in the world. To a certain extent, the number of possible sites depends on the value of energy. To a limited extent, also, the number of sites can be increased by advances in technology, such as improved turbine technology to use lower hydraulic heads, or new construction methods to reduce costs. Primarily, however, the suitability of a site for tidal power development depends on the coastal topography and the height of the tides, both factors outside human control. Distance from centers of power consumption is also important. Possible tidal power sites are enumerated in (Table 4-7)."

North American candidate tidal power sites are listed in Table 4-7. Note that the nearest location of usable tidal power is 300 miles northeast of Boston, MA. It is concluded that tidal power is not a promising candidate for KSC liquid hydrogen production.

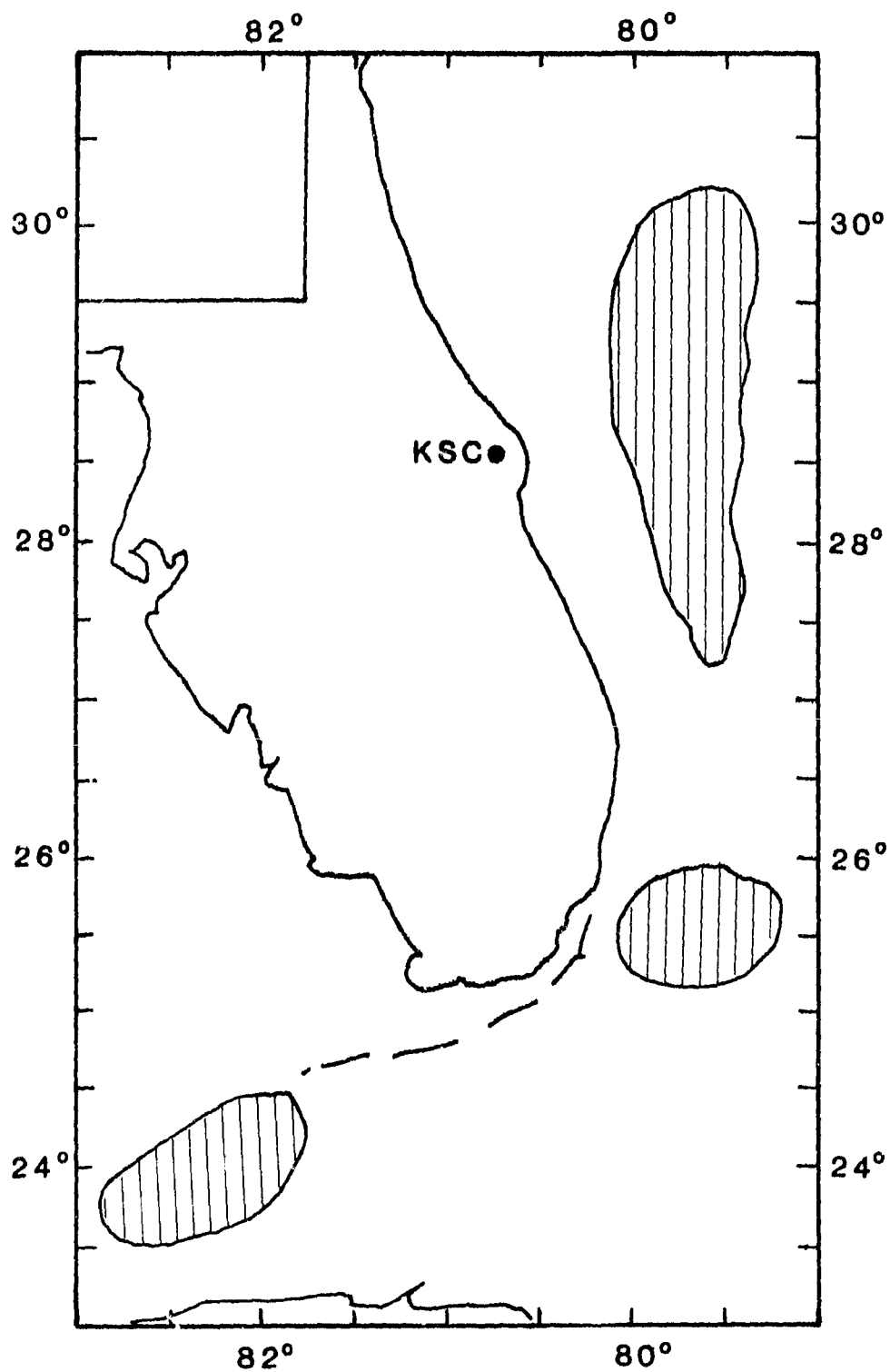


Figure 4-14. OTEC RESOURCES (0-500 METERS,  $\Delta T = 17^{\circ}\text{C}$ )  
(YEAR-ROUND PRESENCE INDICATED)

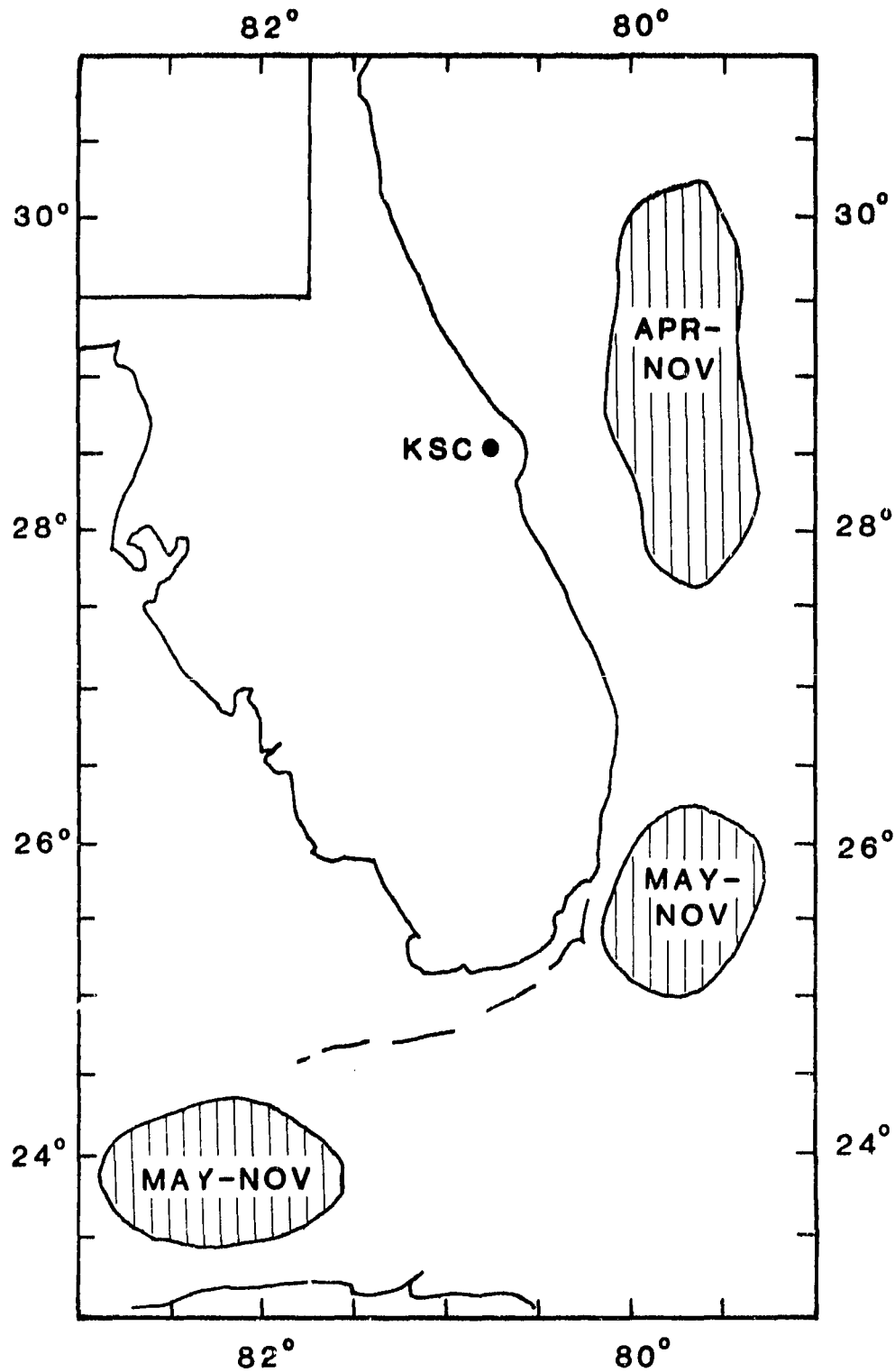


Figure 4-15. OTEC RESOURCE (0-500 METERS,  $\Delta T = 20^\circ\text{C}$ )

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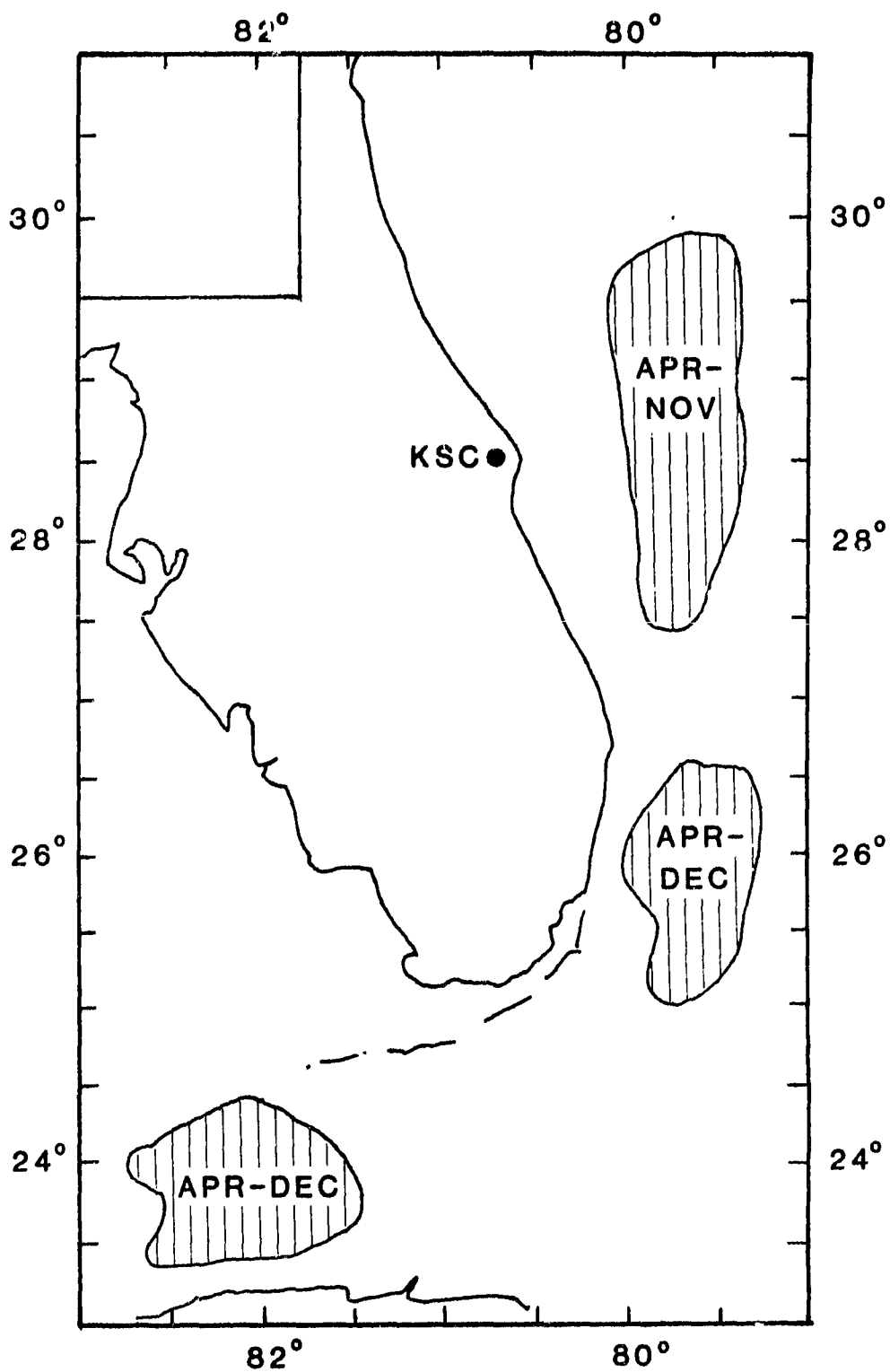


Figure 4-16. OTEC RESOURCE (0-600 METERS,  $\Delta T = 20^{\circ}\text{C}$ )

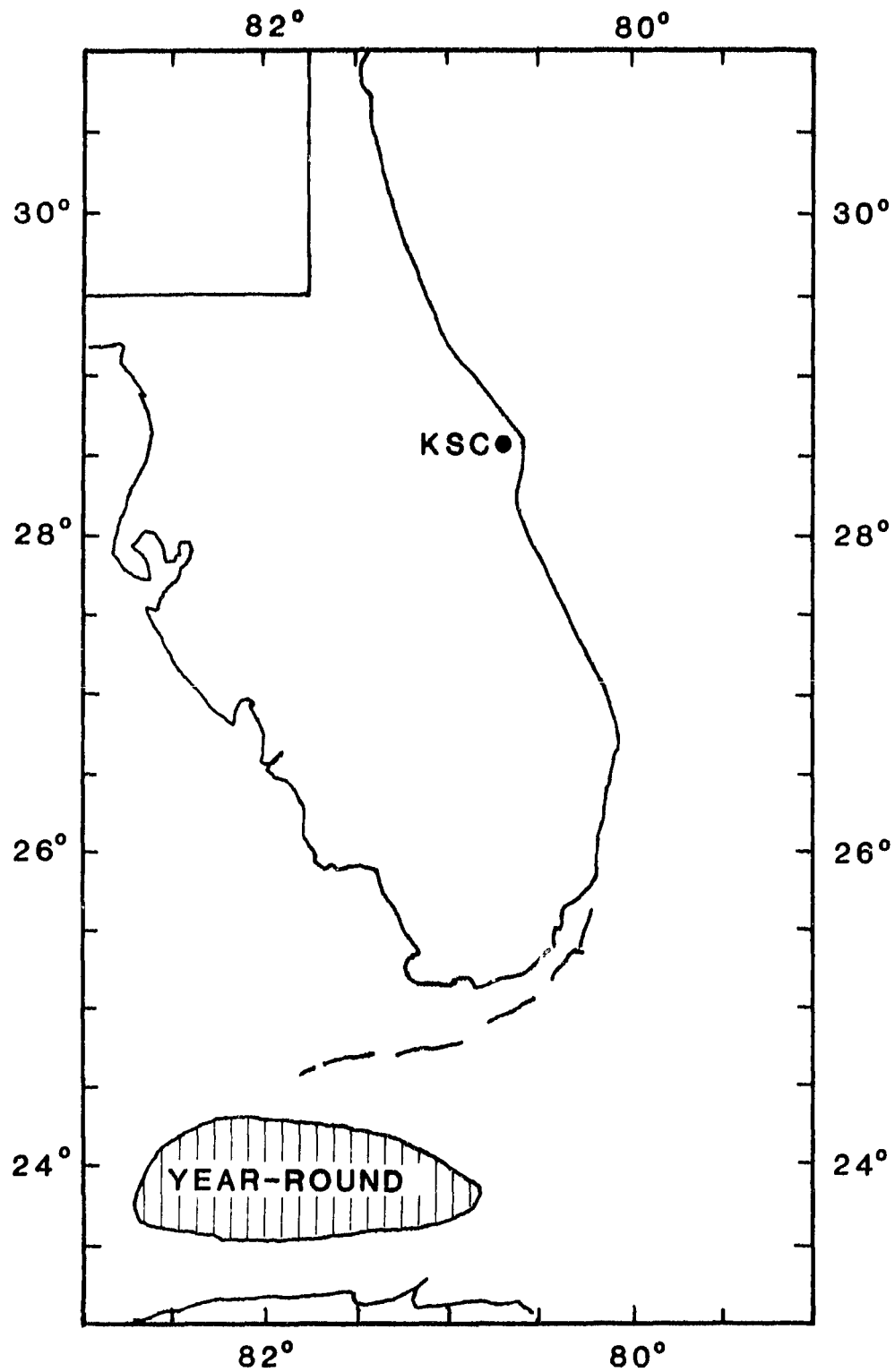


Figure 4-17. OTEC RESOURCE (0-800 METERS,  $\Delta T = 20^\circ\text{C}$ )

Table 4-7. TIDAL POWER SITES

Location <sup>a</sup>	Average Tidal Range (m) <sup>b</sup>	Hydraulic Energy (109 kWhr/year) <sup>c</sup>
North America		
Bay of Fundy		
Passamaquoddy	5.5	16
Cobecook	5.5	6.3
Annapolis	6.4	6.7
Minas-Cobequid	10.7	175
Amherst Point	10.7	2.3
Shepody	9.8	22
Cumberland	10.1	15
Petitcodiac	10.7	7.0
Memramcook	10.7	5.2
Cook Inlet, Alaska		
Knik Arm	7.5	6.0
Turnagain Arm	7.5	13

#### Waves

The estimated wave power available in the coastal waters of the contiguous United States is shown in Figure 4-18. Note that the South Atlantic and Gulf Coast regions have the lowest power density. The nearest useful wave power is off the northwest coast of the contiguous 48 states. Thus, wave-energy systems are not promising for this application.

#### Geothermal

In a 1976 review article (Reference 4-12), Kruger describes the characterization, geographic distribution, extraction, and utilization of the worldwide geothermal resource. The amount of energy stored in the outer 10-km of the Earth's crust is large (about 375,000 times greater than the estimated total U.S. electric power production in 1985). Kruger states:

"...however, geothermal heat in the outer 10-km is too diffuse to be an exploitable energy resource on a worldwide basis. Resources suitable for commercial exploitation may be defined as localized geologic deposits of heat concentrated at attainable depths, in confined volumes, and at temperatures sufficient for electric or thermal energy utilization.

"Major areas of geothermal energy concentrations are associated with tectonic plate boundaries, recent volcanism and orogenesis, and relatively shallow depths to the mantle. Koenig (Reference 4-13) suggests the broad regions shown in Figure (4-19) as logical areas for exploration for geothermal resources. In the United States, the region comprises 13 western states including Alaska and Hawaii."

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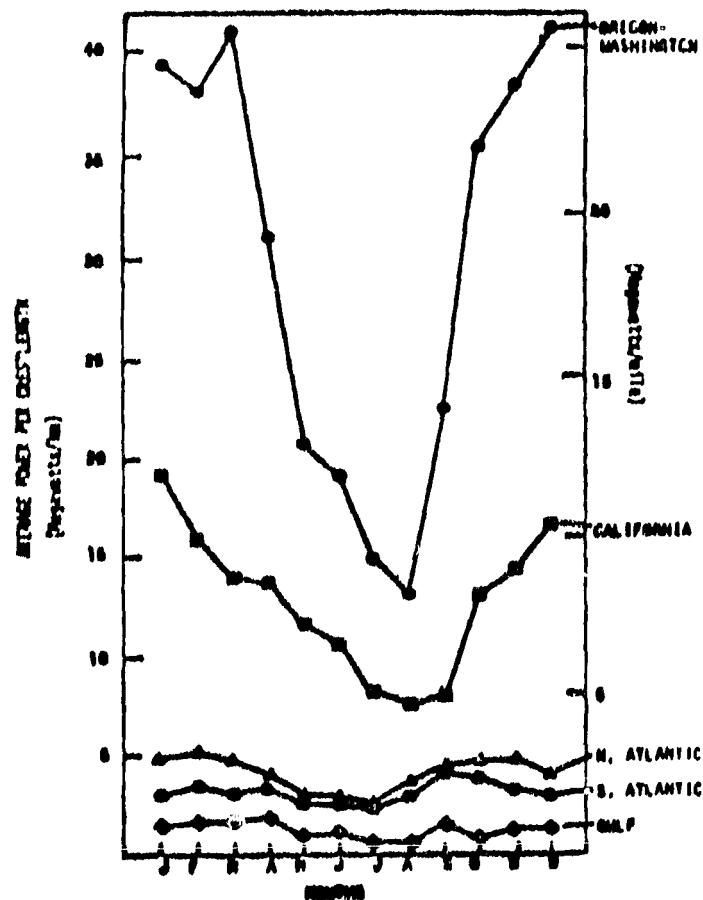


Figure 4-18. MONTHLY AVERAGED WIND-WAVE POWER PER CRESTLENGTH STRIKING THE CONTINENTAL UNITED STATES (Source: Reference 4-11)

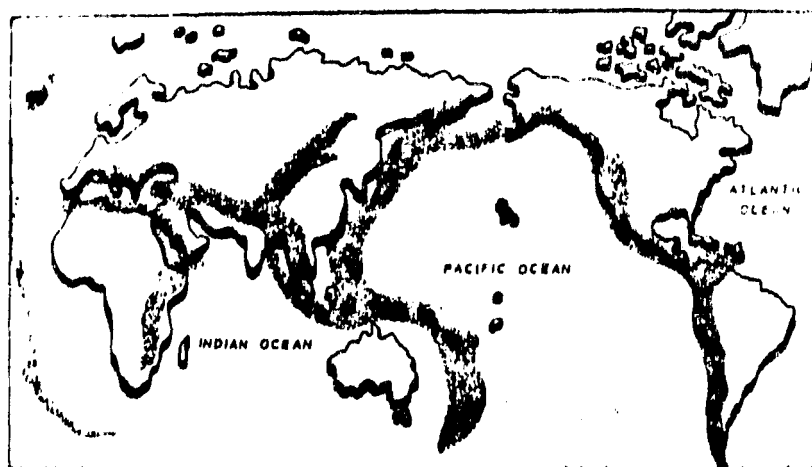


Figure 4-19. REGIONS OF INTENSE GEOTHERMAL MANIFESTATIONS (Source: Reference 4-12)

The following is an excerpt from "EPCOT and Energy" (Reference 4-14):

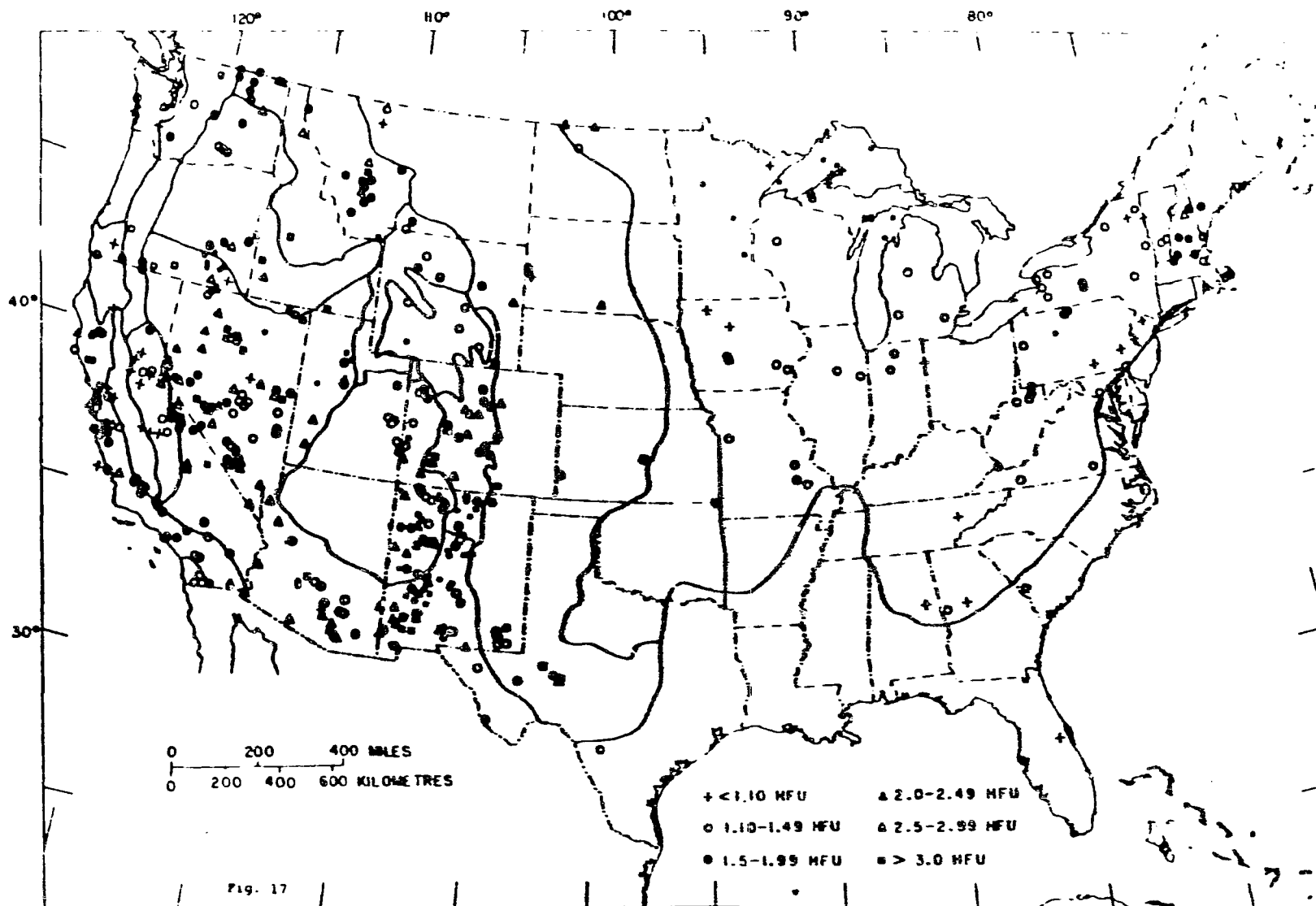
"(A 1975) reference covering the available geothermal resources of the United States is contained in Geological Survey Circular 726 (Reference 4-15, and is shown in Figure 4-20). Due to the sparsity of information contained even in this document, telephone conversations were held with personnel of the Office of Geothermal Information, U.S. Geological Survey (Reference 4-16) and the Department of Geology of the University of Florida in Gainesville (Reference 4-17).

"...The Geological Survey reports one heat transfer measurement having been made near Orlando, Florida (Reference 4-18). This measurement shows a local heat flow of .92 HFU, the unit of measure used by the Geological Survey. Additional unpublished investigations by the University of Florida, Department of Geology personnel, indicates the Florida average will probably be about .8 HFU. It is estimated that the highest value that can be found in Florida will be 1.2 to 1.5 HFU. In order to be of even marginal interest, a geothermal reservoir should be characterized by 2.5 to 3 HFU.

"In terms of the temperatures available, the minimum required for any practicable steam applications would be approximately 300°F. It is the opinion of the University of Florida staff that drilling depths would have to exceed 4-km if such a temperature is to be reached. There is no information available to indicate the probability of success of such a drilling operation. With such depth being required, pump work requirements would cut heavily into any power output potential."

Hence, geothermal energy-based systems do not appear of interest to Florida-sited liquid hydrogen production systems.





Uncovered heat flow (e.g., measurements to the United States). Measurements obtained to date less than 150 in depth (indicated by dots) are not considered reliable as a group and therefore are not used as to value. Most sources of earlier data may be found in a compilation by Lee and Frede (1968).

Figure 4-20. AVAILABLE GEOTHERMAL RESOURCES OF THE UNITED STATES AS OF 1975  
(Source: Reference 4-15)

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- 4-14. "EPCOT & Energy. Part 2. Evaluation of Alternatives-Recommended Energy System," prepared for WED Enterprises by Escher Technology Associates, St. Johns, MI, November 1975.

- 4-15."Assessment of Geothermal Resources of the United States-1975," U.S. Geological Survey Circular 726, U.S. Geological Survey, National Center, Reston, VA, 1975.
- 4-16.Private communication with Dr. D. Klick, U.S. Geological Survey, Geothermal Energy Information Office, October 1975.
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## 5. IDENTIFICATION OF AVAILABLE LAND

### Inventory of Available Land

The purpose of this section is to identify dispersed and contiguous land on the KSC property that is presently undeveloped and that is potentially available for development of a hydrogen production system. The land requirements for solar direct-conversion system options is noted to be the order of 2 km<sup>2</sup>.

### Floodplains and Wetlands

A primary constraint to the development of land at KSC is the existence of wetlands and the 100-year floodplain. Nearly 80% of the KSC land area is floodplain or wetland. In accordance with Executive Order (EO) 11988 "Floodplains Management" and EO 11990 "Protection of Wetlands," it is KSC policy to site facilities in floodplain and wetland areas only when no reasonable alternative exists. In the past, no reasonable alternative has existed for siting such facilities as the Shuttle Landing Facility, Launch Pads 39A and 39B, and the crawlerway and access roads. In those instances, it was necessary to conduct fill operations to raise the immediate site above the 100-year floodplain and to reclaim the wetland areas. For this project, the cost of site development fill operations presents a significant economic disincentive to developing floodplain and wetland areas. Since it is anticipated that there is sufficient KSC land available outside of these areas, a reasonable constraint imposed on this project is to only select sites outside of the 100-year floodplain and wetland areas. Figure 5-1 is a map of the 100-year floodplain at KSC. The 100-year floodplain contains nearly all of the wetland areas; however, in specific instances and due to local groundwater conditions, wetlands occur outside of the 100-year floodplain. These cases must be treated on an individual basis and are beyond the scope of this study. The lighter and undeveloped inland areas showing in Figure 5-1 constitute the inventory of available land at KSC for the hydrogen production system.

### Merritt Island National Wildlife Refuge and Canaveral National Seashore

NASA-KSC has entered into agreements with the U.S. Fish and Wildlife Service (FWS) and the National Park Service (NPS) for the management and operation of land and water areas not specifically required to support the space program. The FWS manages all such land at KSC as the Merritt Island National Wildlife Refuge except for that land surrounding the Mosquito Lagoon which is managed by the NPS as Canaveral National Seashore. These areas are shown in the map in Figure 5-2.

### Endangered and Threatened Species Habitat

In support of the preparation of the most recent Environmental Impact Statement (EIS) for KSC Shuttle Operations (Reference 5-1), an extensive study was performed of the endangered and threatened flora and fauna species at KSC. That study identified areas of concentration, critical habitats, breeding areas, and nesting areas for 21 fauna species that are listed by either state or federal authorities as being endangered or threatened. Those species identified are listed in Table 5-1 from the EIS. Reference is made here to the extensive habitat maps contained in the EIS. In addition, that

ORIGINAL MAP  
OF POOR QUALITY

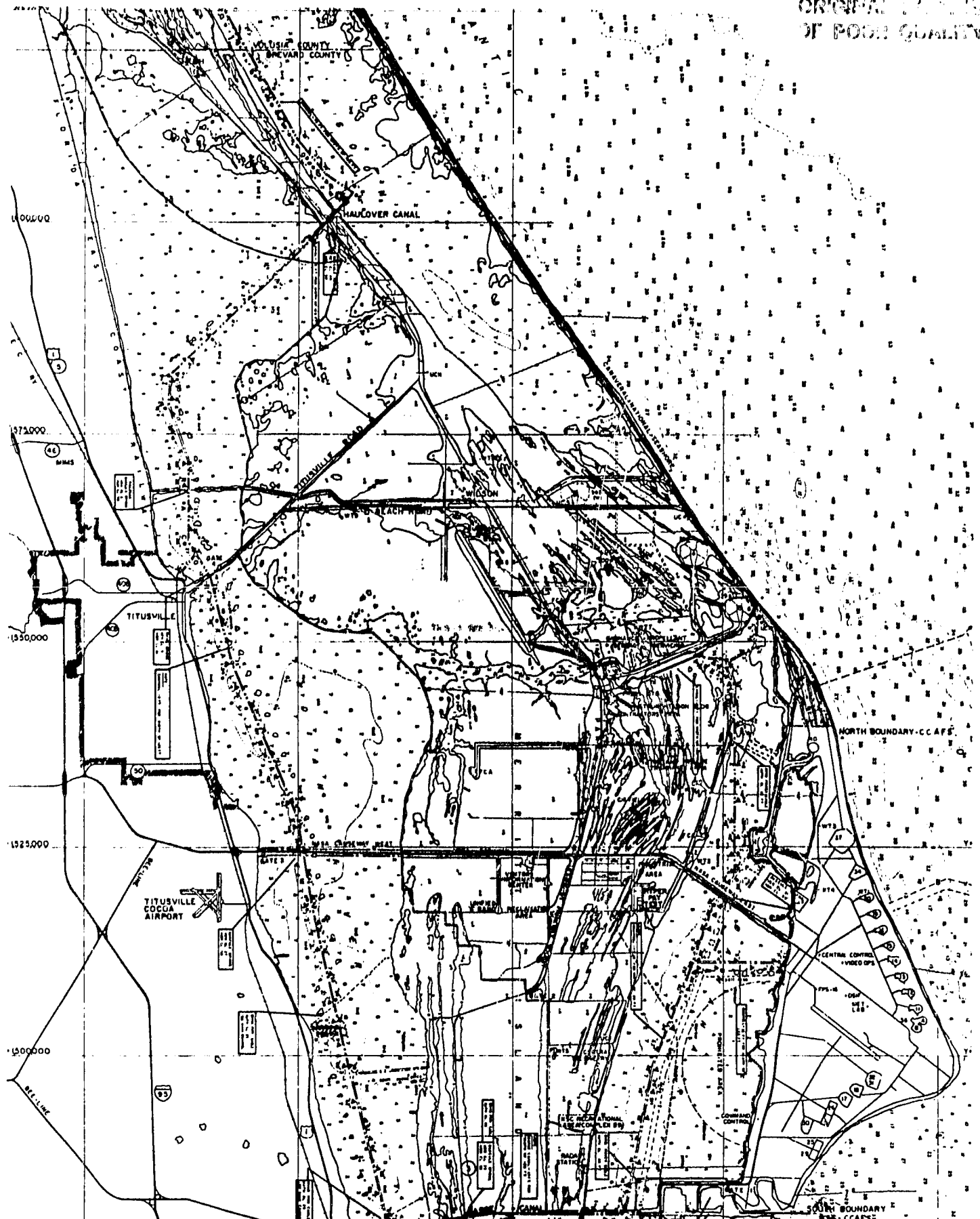


Figure 5-1. KSC TOPOGRAPHY AND 100-YEAR FLOODPLAN MAP (Source: Reference 5-1)

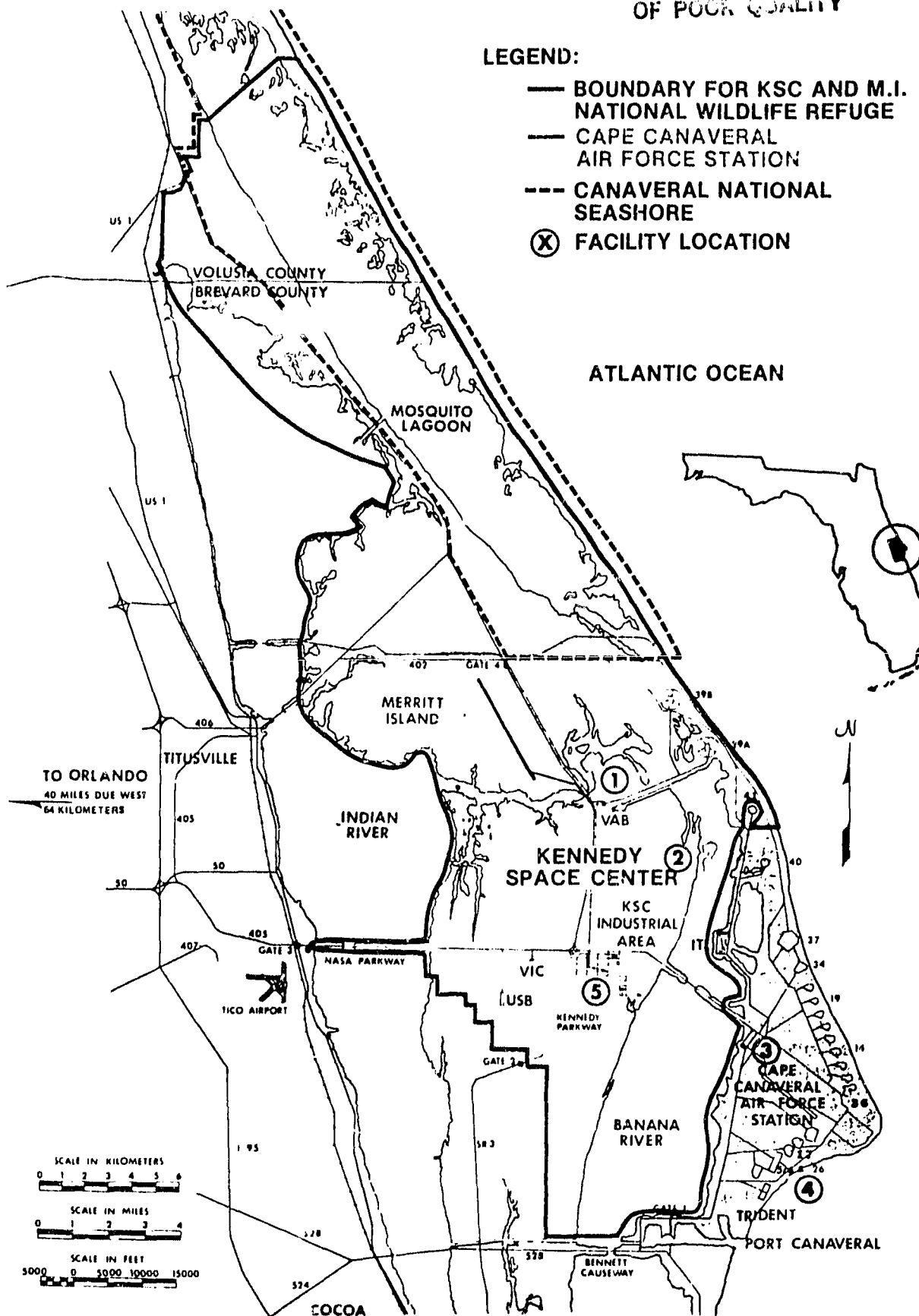


Table 5-1. KSC AREA ENDANGERED (E) AND THREATENED (T) SPECIES - 1978  
(Reference 5-1)

	Status			Population - M.I. National Wildlife Refuge			
	Fed.	State	Breed	Spring	Summer	Fall	Winter
Florida Manatee	E	T	Yes	30-50	30-80	50-80	0-50
Eastern Brown Pelican	E	T	Yes	1000-1400	1000-1400	800-1100	800-1100
So. Bald Eagle	E	T	Yes	12-15	4-6	10-12	10-12
Arctic Peregrine Falcon	E	E	No	4-12	0	12-20	4-8
Dusky Seaside Sparrow	E	E	Yes	2	2	2	2
Atlantic Ridley Turtle	E	E	No	5-10	5-10	5-10	5-10
Amer. Alligator	T	T	Yes	5000	5000	5000	5000
Atlantic Salt Marsh Snake	T	E	Yes	*	*	*	*
Ea. Indigo Snake	T	T	Yes	*	*	*	*
Atlantic Loggerhead Turtle	T	T	Yes	400-600	1000-1200	400-600	400-600
Atlantic Green Turtle	E	E	Yes	100-150	110-160	110-150	100-150
Gopher Turtle		T	Yes	13800	13800	13000	13000
Wood Stork		T	Yes	250-350	50-300	200-500	200-500
Osprey		T	Yes	10-20	20-40	20-30	10-20
Southeastern Kestrel		T	No	0-10	0	20-50	30-50
Least Tern		T	Yes	100-300	300-400	50-100	0
Roseate Tern		T	No	*	*	*	*
Florida Scrub Jay		T	Yes	*	*	*	*
Am. Oystercatcher		T	No	*	*	*	*
Magnificent Frigatebird		T	No	0	10-15	5-10	0
Florida Mouse		T	Yes	*	*	*	*

\* Census inventory or inferential data now being collected for these species.

study identified 11 flora that are classified as endangered, threatened, rare, or of special concern. Table 5-2 (Reference 5-1) lists those flora species. In accordance with the Coastal Zone Management Act of 1972, the Florida Bureau of Coastal Zone Planning has identified several classifications of land and water areas at KSC that should be conserved. Those areas are identified in Figure 5-3.

Table 5-2. ENDANGERED AND THREATENED FLORA (Reference 5-1)

<u>Common Name</u>	<u>Taxonomic Classification</u>	<u>Status - Florida List</u>
Sea Lavender	<i>Tournefortia gnaphalode</i>	Endangered
Coontie	<i>Zamia integrifolia</i>	Threatened
Hand Fern	<i>Ophioglossum palmatum</i>	Endangered
Pond Apple	<i>Annona glabra</i>	Endangered
Satin Leaf	<i>Chrysophyllum oliviforme</i>	Endangered
Curtis Milkweed	<i>Asclepias curtissii</i>	Threatened
Golden Leather Fern	<i>Acrostichum aureum</i>	Rare
Water Sundew	<i>Drosera intermedia</i>	Rare
Florida Peperomia	<i>Peperomia obtusifolia</i>	Rare
Red Mangrove	<i>Rhizophora mangle</i>	Special Concern
Black Mangrove	<i>Avicennia germinans</i>	Special Concern

#### Soil Classification

The soil types found in the KSC area are shown in Figure 5-4. Most of the undeveloped land out of the floodplain is characterized by Myakka, Eau Gallie, and Immokalee soils. These soils can be described as nearly level, poorly drained, and sandy to a depth of 40 inches with loam below. Principal flora is saw palmetto, wiregrass, and slash pine.

#### Developable Sites

The undeveloped land outside of the floodplain as indicated in Figure 5-1 consists of three substantial land areas where a large hydrogen production system could be deployed. These large sites are identified on Figure 5-5 as Sites A, B, and C and are discussed below. For scale, the gridlines on Figure 5-5 are on 7.6 km (4.7 miles) centers. Each block defined by adjacent N-S and E-W gridlines encompasses 58 square kilometers (22 square miles).

It is apparent that there are a substantial number of small sites throughout the KSC facility either within the three large sites identified here or in smaller areas adjacent to or within major developed areas. These small sites, which will not be discussed further here, might be available for a hydrogen production system that utilized dispersed subsystems such as solar photovoltaic panels, electrolyzer, liquefier, and storage. Sites "A, B, and C" are identified as prospective locations as described next.



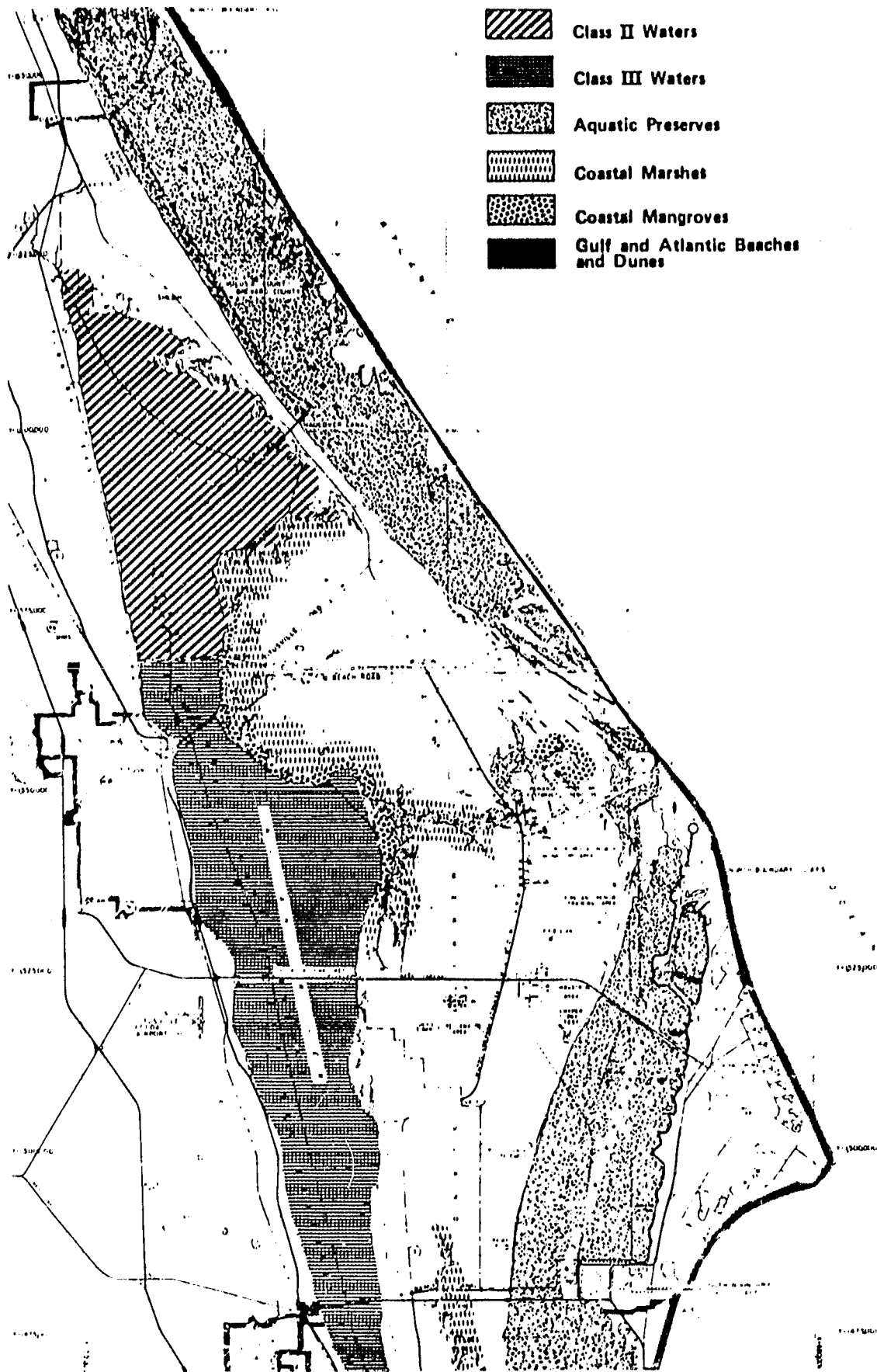
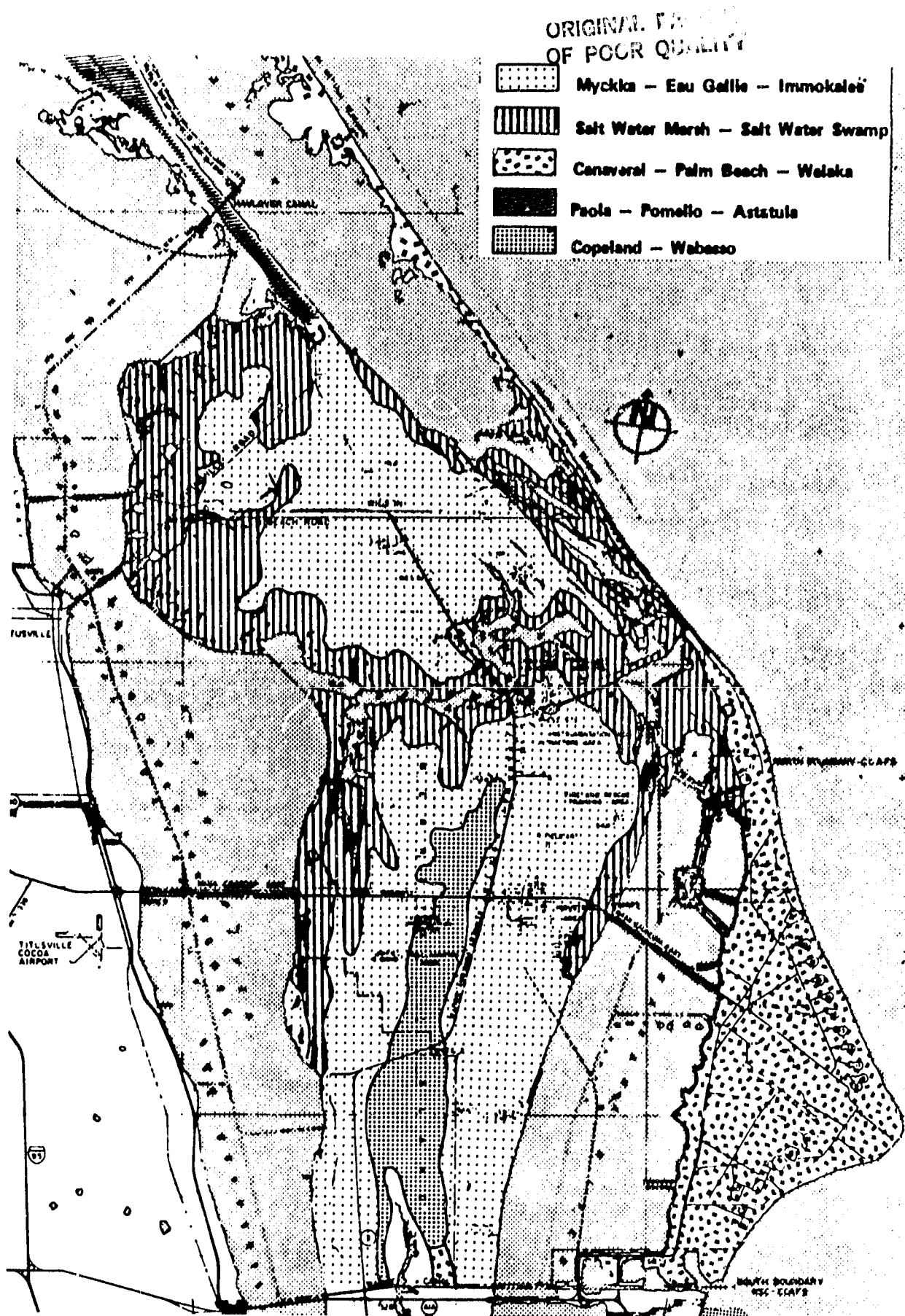


Figure 5-3. KEY ENVIRONMENTAL FEATURES: CAPE CANAVERAL-MERRIT ISLAND LAND MASS (Source: Reference 5-1)



This is a detailed topographic map of the Titusville, Florida area. The map shows the Titusville-Cocoa Airport, the Titusville Canal, and the Hawcover Canal. The map is oriented with North at the top. The map includes labels for 'TITUSVILLE COCOA AIRPORT', 'TITUSVILLE CANAL', 'HAWCOVER CANAL', and 'TITUSVILLE'. It also shows 'NORTH BOUNDARY-CC A1' and 'SOUTH BOUNDARY-CC A1'. The map is oriented with North at the top and includes a scale bar at the bottom.

5-8

### Site A

Site A is a large area of approximately 20-km<sup>2</sup> bounded on the north by wetlands adjacent to Mosquito Lagoon, on the east by wetlands adjacent to Launch Pad (LP) 39B, on the south by Banana Creek, and on the west by wetlands adjacent to the Shuttle Landing Facility. The site is bisected by a spur of the Florida East Coast Railway, Kennedy Parkway North, and by Beach Road. Positive aspects of the site include:

- Good accessibility by road and rail
- Relatively flat
- Within 1-km of LP 39B at several points
- Presents few problems with regard to endangered species habitats.

Negative aspects of the site include:

- Low public visibility
- At least 4-km (at the closest point) from 115-kV FPL feeder
- At least 4-km (at the closest point) from the thermal and electric load centers and utilities at the VAB
- Construction in the northern reaches of the site may be restricted regarding allowable height due to the Shuttle landing approach path
- Not accessible by barge.

### Site B

Site B is a large area of approximately 10-km<sup>2</sup> bounded on the north by the wetlands immediately adjacent to barge canal and the VAB press site, on the east by wetlands adjacent to Banana River, on the south by wetlands adjacent to the KSC Industrial Area, and on the west by wetlands and Kennedy Parkway North. Site B includes the proposed location of the Polygeneration Facility, presently under study at KSC. Positive aspects of the site include:

- Relatively flat
- High public visibility
- Less than 1-km from the thermal and electric load centers and utilities at the VAB in the UA
- Good accessibility by road and barge
- Less than 1-km from the FPL feeder at the VAB
- Few problems with regard to endangered species habitats.

Negative aspects of the site include:

- Not readily accessible by rail
- Nearly 7-km distant from LP 39.

### Site C

Site C is a very large, flat land area encompassing approximately 30-km<sup>2</sup> bounded on the north by the KSC Industrial Area, on the west by Kennedy Parkway South, on the south by a barge canal, and on the east by the wetlands adjacent to Banana River. The northern end of Site C had earlier been identified as a prospective test site for solar energy research. The KSC Recreational Area Complex 99 is situated in the southern end of Site C. Several roads cross the site from east to west. Positive aspects of the site include:

- Readily accessible by road
- Accessible on the northern end by rail
- Accessible on the southern end by barge to the Canaveral Harbor
- Immediately adjacent (on the north end) to the FPL 115-kV feeder and KSC substation in the Industrial Area
- Immediately adjacent (on the northern end) to thermal load centers and utilities at the Industrial Area
- Some public visibility if system is close to Kennedy Parkway South at the intersection with NASA Causeway West.

Negative aspects of the site include:

- The thermal heating load at the Industrial Area will be mostly met by the incinerator project currently underway, hence no "market" for facility rejected heat
- The north end is not accessible by barge
- Nearly 8-km distant from the VAB and UA
- Nearly 14-km distant from LP 39.

#### Reference Cited in Section 5

- 5-1. "Environmental Impact Statement for the Kennedy Space Center (1978-1979 Revision)," Final Report prepared for the National Aeronautics and Space Administration, October 1979.

## 6. SCREENING OF TECHNOLOGY CANDIDATES

### General Approach

The scope of work of this study requires that a survey of methods and selection of viable candidates for providing liquid hydrogen for U.S. space launch vehicles independent of fossil fuels beginning as early as 1987 to 1992 or otherwise whenever the particular technologies and economic trade-offs appear favorable. The "viable candidates" identified will be used to guide and support conceptual design of at least two different renewable resource systems. Thus, a screening process of the numerous technological candidates must be carried out in such a fashion as to provide two selected candidates for the conceptual design portion of the study.

The first step considered is to assess the status of technological development for each candidate technology. The Electric Power Research Institute (EPRI) Technical Assessment Guide (Reference 6-1), as an exemplary guide, suggests the following categories:

1. No system hardware development
2. Concept supported by laboratory studies and initial hardware development
3. Concept supported by small pilot facility
4. Concept verified by integrated demonstration plant
5. Significant commercial experience (more than 5 commercial plants).

Using this categorization, certain specific guidelines are believed reasonable and prudent. Only those technologies in the fourth and fifth classes will be considered for the 1987 target date. Technologies in the second and third classes may be appropriate for a 1992 target date, although some of these may fall into the "beyond 1992" category. Technologies in the first class will be placed automatically in the "beyond 1992" category.

Candidate systems can then be conceptually synthesized from the technologies meeting the 1987 and 1992 target dates. The second level of screening will then be performed on the comparative economics of thus-identified systems. Technologies falling into the post-1992 category are judged generally not capable of economic assessment at any significant level of accuracy.

For each technology, a brief description is provided. For older candidates, references are provided wherein back-up details can be obtained. For some of the relatively new candidates, a more detailed explanation can be found in the Appendices of this document.

The current status of the technology is review and an assignment to one of the five EPRI categories is made. Based on recent information, each technology is assigned an applicability date of 1987, 1992, or beyond-1992. The primary resource required for each such energy conversion technology is identified and the presence or absence of the resource at KSC is noted. For resources not present at KSC, an approximate distance to the nearest location is estimated.

C - 2

Section 4 of this document indicates lack of a developable resource sufficiently near KSC to warrant further attention in this area.

### Solar Resource

Section 4 showed that the solar resource is abundant at KSC for global (or diffuse) insolation suitable for non-concentrating systems. Direct insolation, while present, is by no means as intense as in the American Southwest. Concentrating systems capable of using the intermittent direct radiation are possible but a careful analysis will be necessary to ascertain technoeconomic feasibility.

### Nuclear Energy

#### Fission Burner Reactor

These are in widespread use in the U.S. and elsewhere but at sizes far too large at ca. 1000-MWe for the KSC requirement alone. Recently, design studies have been completed for much smaller modular high-temperature, gas-cooled reactor (HTGR; Reference 6-2) consisting of modules which can be factory prefabricated and assembled into a plant with high reliability due to a number of modules in parallel. Work is proceeding in Germany at a substantially higher level on this concept than elsewhere (Reference 6-3). A brief overview of this approach is contained in Figure 6-1.

One, or possibly two, of these modular HTGR modules would be appropriate insofar as sizing is concerned for a KSC-based reactor system to produce hydrogen, especially if the units can be further downsized somewhat. For the KSC requirement being addressed, about a 15-MWe or 50-MWt nuclear system would be fitting. Conversations with Dr. Garth Leeth of GE (Reference 6-4) suggest that the modules likely could be fabricated down to 40-50 MWt. He stressed the intrinsic high-level of safety of operation, as well as the basic modular design leading to high reliability.

A time-frame of 1992, at the earliest, appears appropriate for "first-availability" of such systems. No further developmental requirements are claimed to be needed for operation at 700°C-800°C. Competitive costs must, however, await orders in commercial quantities. With no market need presently in general view, the time-availability for a KSC application is highly uncertain.

#### Fission Breeder Reactors

A recent review in High Technology (Reference 6-5) suggests that no commercial breeder reactor will be operating in the United States in this century. The proposed demonstration breeder at Clinch River, Tennessee, is beset with political policy problems unlikely to be resolved shortly. Even if progress goes according to the current (optimistic) schedule, the five-year demonstration phase will not be complete prior to 1994.

The long time until potential commercialization effectively rules out this technology for the KSC application under consideration.

GENERAL ELECTRIC

### MODULAR HTGR PLANT PERFORMANCE (PER MODULE)

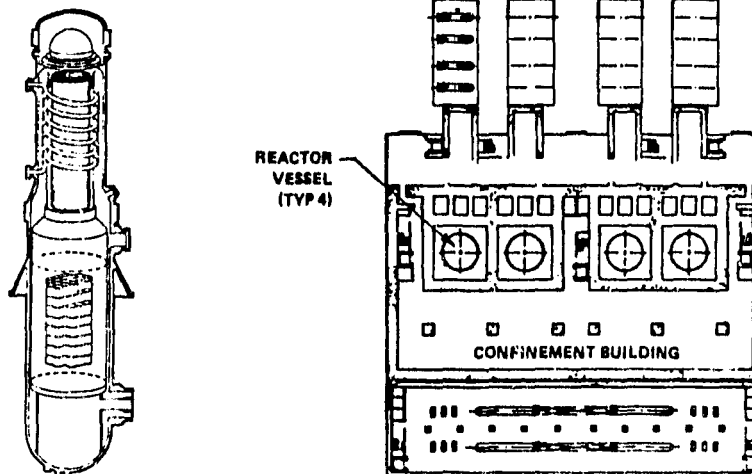
REFORMING MRS		SC/C MRS	
CORE POWER, MW <sub>T</sub>	250	CORE POWER, MW <sub>T</sub>	300
REFORMER/SG DUTY, MW <sub>T</sub>	139.5/113.0	GROSS ELECTRICAL, MW <sub>E</sub>	40.6
REFORMER POWER SPLIT, %	55	NET ELECTRICAL, MW <sub>E</sub>	34.8
PIPE LINE ENERGY, MW <sub>T</sub>	147	PIPE LINE ENERGY, MW <sub>T</sub>	261
NET ELECTRICAL, MW <sub>T</sub>	11.5	PIPE LINE STEAM CONDITIONS, %/PSIA	730/875
EXPORT PH FRACTION, %	53	EXPORT PH FRACTION, %	87
PLANT EFFICIENCY, %	23.4	PLANT EFFICIENCY, %	28.5

ADVANCED REACTOR SYSTEMS DEPARTMENT

GE-377-14

GENERAL ELECTRIC

### GAS COOLED THERMAL REACTOR PROGRAM MODULAR HTGR SYSTEM FEATURES



ADVANCED REACTOR SYSTEMS DEPARTMENT

GE-377-27

Figure 6-1. SUMMARY INFORMATION ON MODULAR HIGH TEMPERATURE GAS-COOLED REACTOR (HTGR) SYSTEMS  
(Source: General Electric Company)



## Fusion Reactors

Four large Tokamak reactors, large enough to achieve breakeven operation, are in operation or under construction (Reference 6-6). The reactor at Princeton has operated, a British reactor is expected to be operable soon, and a Japanese and Russian version are expected in 1985. The first laboratory breakeven experiments at the Princeton TFTR are scheduled for 1986.

From laboratory breakeven (the output of fusion power equal to the input power) to commercialization is a long process, eliminating this technology from serious consideration for the pre-2000 time-frame of interest.

## Geothermal Energy

Section 4 of this document indicates lack of a developable resource sufficiently near KSC to warrant further attention in this area.

## Solar Energy

### Biophotolysis

Biophotolysis is defined here collectively as those processes and systems (based on those processes) that use biological mechanisms to convert solar radiation to hydrogen. The use of biological processes to generate hydrogen-containing compounds requiring further processing are discussed in another section. The status of this technology through 1979 is documented in "Solar/Hydrogen Systems Assessment, Vol. 2, Part 1 (Reference 6-7). Recent activity was characterized in a World Hydrogen Energy Conference-IV paper (Reference 6-8) documenting work done at Solar Energy Research Institute (SERI). The abstract follows:

Certain photosynthetic bacteria (PSB), for example, *Rhodospseudomonas capsulata*, evolve hydrogen when placed in an anaerobic environment with light and a suitable organic substrate. An engineering effort to use such bacteria for large-scale hydrogen production from sunlight is described in this paper. A system to produce 28,000 m<sup>3</sup>/day (1 x 10<sup>6</sup> ft<sup>3</sup>/day) of hydrogen has been designed on a conceptual level and includes hydrogen cleanup, substrate storage, and waste disposal. The most critical component in the design is the solar bacterial reactor. Several designs were developed and analyzed. A large covered pond concept appears most attractive. Cost estimates for the designs show favorable economics.

The study team contacted author Herlevich in December 1982 for additional information. The highlights of the discussion were:

- Target process availability timing is 5-10 years, 8 years nominal which is predicated on continuing DOE funding (now in some question)
- Work to date is with indoor, small-scale (4 x 8 ft) reactors; outdoors applications foresee two major problems: temperature control and other-species intrusion
- SERI researchers are still attempting to understand the basic photosynthetic processes involved, e.g., dark-reaction processes, need for genetic engineering measures.

According to Ms. Herlevich, several engineering developments are still necessary before outdoor implementation in a prototype mode can be attempted:

1. The reactor design must self-modulate temperature in the 32°-40°C range. Below 32°C, hydrogen production is negligible, while above 40°C, the organisms die. Existing work has utilized external sources of energy to stabilize temperatures, probably not practicing in an operating system.
2. An inexpensive hydrogen-impermeable cover to aid collection must be developed.

Also, the economics of hydrogen production have not included the cost of obtaining and/or transporting the substrate (food) for the culture, nor removal of waste products. The scheme is still being thought of principally as a "clean up" process with hydrogen output as a valued byproduct.

Concerning the published estimates of 5% and 10% conversion efficiencies, and how these efficiencies were defined, SERI stated that their efficiency is based on total irradiation from a tungsten light source, fairly closely approximating the full solar spectrum. Particularly, at 10%, it appears that SERI is planning on achieving markedly higher efficiencies than other investigators of similar biological hydrogen processes, e.g., Dr. Mitsui at Miami.

A key point made relates to "feeding the bugs:" at SERI, the photosynthetic organisms are supplied organic acids up to C9. Fermented peach pits, possibly orange peel residues, etc., are usable. Such a feedstock requirement lends the view noted above that the reacting organisms provide a "clean-up service" while producing hydrogen as a credit byproduct.

In other words, there should logically be a clean-up/purification need at the hydrogen production site. This seems doubtful at KSC, bringing into focus the need for a large organic material feedstock requirement and waste removal as well as basic insulation requirements.

General impressions are that this process is still strictly at the controlled-laboratory stage with some basic unanswered questions, e.g., temperature control implications, other-species invasion and defeat of the process. Another serious question is that of DOE financial support continuing at sufficient levels to ensure progress. Also, the waste-stream clean-up with hydrogen byproduct image is worrisome for our application. Under the best circumstances, this process is certainly not deployable in the 1987-1992 time-frame, and probably not prior to 2000.

By way of an attempt to get a "peer expert" opinion on the SERI effort reviewed above, we contacted Dr. A. Mitsui at the University of Miami, relating briefly what we had heard from SERI. Dr. Mitsui has a small grant from KSC to continue certain aspects of his work with hydrogen production from blue-green algae which he has been concentrating on for at least a decade. Although he anticipates distinct progress in this general field (microscopic organism production of hydrogen) in, say, 5 years, he feels that the projection of a deployment stage in any engineering detail is premature. He thinks in terms on one-half- to 5-liter laboratory batches, which he attempts to keep alive and productive for the order of weeks under laboratory conditions.

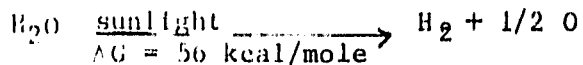
Overall conclusion on the biophotolysis process:

- Not applicable to a 1987-1992 field deployment
- questionable for ca. 2000 application.

Technology Status Ranking is 2--supported by laboratory studies. The primary resource--direct and global insolation--is available at KSC.

#### Photolysis and Photocatalysis

The objective of the photolysis (non-catalytic) and photocatalysis approach is the basic water splitting reaction:



The basic problem of accomplishing this process by the direct illumination of water with solar radiation is described by Brinkworth (Reference 6-9):

"It is found that to dissociate one water molecule requires about 3 eV of work. If this were to be provided by a radiation photon, that photon would have to have a wave length of less than 0.4  $\mu$ m (400 nm). Only about 3% of sunlight at sea level has wavelengths in this region. Even this might be worthy of exploiting if it could be done cheaply enough. The difficulty is that this process cannot take place, even at an efficiency of this order, because water is nearly transparent at these wavelengths."

Thus, the initial problem becomes that of finding some method of decreasing the transparency of water to photons with the required energy level. This requires the use of some approach that "sensitizes" the water system. This sensitizer can also be achieved, its cost and efficiencies are the next points of concern.

The technoeconomic feasibility of photocatalysis of water, with the objective of producing hydrogen, cannot be determined at this time. Aside from the general problem of achieving efficient photocatalytic processes, the materials used in processes presently being investigated often involve rare metals, e.g., Ruthenium. The economic practicality will be dependent upon the amount of such materials that are required for such systems, and to what extent less expensive metals such as cobalt can be used. These processes are placed in Technology Status Ranking 2--applicability is judged post-2000. The insolation resource is present at KSC.

## Photoelectrocatalysis and Photoelectrolysis

The following is excerpted from "Solar/Hydrogen Systems Assessment, Vol. 11, Part 1," a JPL study done by E:F Technology, Inc. (Reference 6-7).

"The basic liquid electrochemical cell consists of some form of container, conducting anode and cathode pieces, and an easily-ionizable electrolyte in liquid form. Similar cells can be constructed with other electrolyte forms. The general structure of such cells is found in many different applications, including electroplating, electrolysis, energy storage, and, of direct interest here, energy conversion systems.

"An elementary form of such a cell can be constructed of two identical electrodes of a conducting material which can be immersed in an appropriately-ionized solution. It is obvious that such a system will be stable unless some situation causes the activity near either of the electrodes to be different from the other. The ability of light, incident on one electrode, to produce this change in activity, and thus to induce electron flow in the external circuit, was found by A.C. Becquerel in 1839.

"Additional inspection of the system discloses that two different types of photoelectrochemical cells exist--those in which the light energy acts on the interface between the electrolyte and the electrode and those in which the light energy acts on the electrolyte itself. Modern photoelectrochemical cells, involving or not involving components that can be defined as catalysts, are the former type. Cells in which the light energy acts on the electrolyte are photogalvanic cells."

During 1982, work at the University of California Berkeley (UCB) and at Texas A&M received attention in the press (References 6-10 through 6-12). The UCB work involved iron oxide electrodes in a solution of water and sodium sulfate. The electrodes are "doped"--one with Silicon and the other with magnesium. The efficiency in the laboratory is only (as yet) 0.05%, which implies an area of about 100 Km<sup>2</sup> to provide 10 million gallons of liquid hydrogen per year.

The Texas A&M work reported higher efficiencies, on the order of 10%, using p-type Silicon photocathodes in an acid solution. Photocathode stability is still a decided problem.

Both studies are still definitely only in Technology Status Ranking 2--supported by laboratory studies, and are clearly placed in the post-1992 time-frame for this study. The resource--direct and global insolation--is readily available at KSC.

## Photovoltaic

A photovoltaic cell is a solid state device which converts light or solar radiation directly into electricity. Typically, the solar cell is a thin, flat wafer of semiconductor material such as silicon although a variety of other materials are under development or close to commercialization.

The photovoltaic effect occurs when a junction of materials with different electrical properties is illuminated and conditions are arranged so that a small, permanent electric field is created across the region of the junction. Light, exciting electrons to a higher energy potential, causes a voltage to appear between the top and the bottom of the cell. The small field in the junction prevents this energy from being dissipated within the device. Thus, the electrons can be made to flow through an external circuit. This process will continue as long as the cell is illuminated.

Following initial development for space applications, standard nomenclature evolved as photovoltaic devices were adapted to terrestrial use. For example, many cells connected together and encapsulated in a single unit constitute a module, whereas several modules connected together are known as a panel. Finally, a field of panels made up of modules and panels is known as an array (see Figure 6-2).

This technology is under full commercialization at present. A recap of production and price trends is provided in Figure 6-3. A 100-MW array is planned by the Sacramento Municipal Utility District (Reference 6-13), with the first 1-MW subarray being acquired for less than \$5/peak watt (uninstalled) (Reference 6-14). Another large array of 16-MW is planned by ARCO Solar in San Louis Obispo County, California, utilizing concentrating mirrors and tracking heliostats (Reference 6-15).

The Technology Status Ranking is 5--significant commercial experience. Sufficient industry capacity should exist to allow use of this technology at KSC in 1987. The primary resource--global insolation--is abundant at KSC.

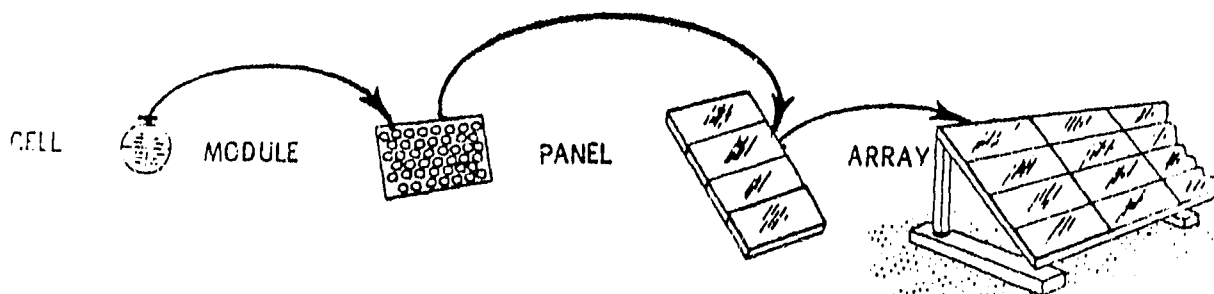
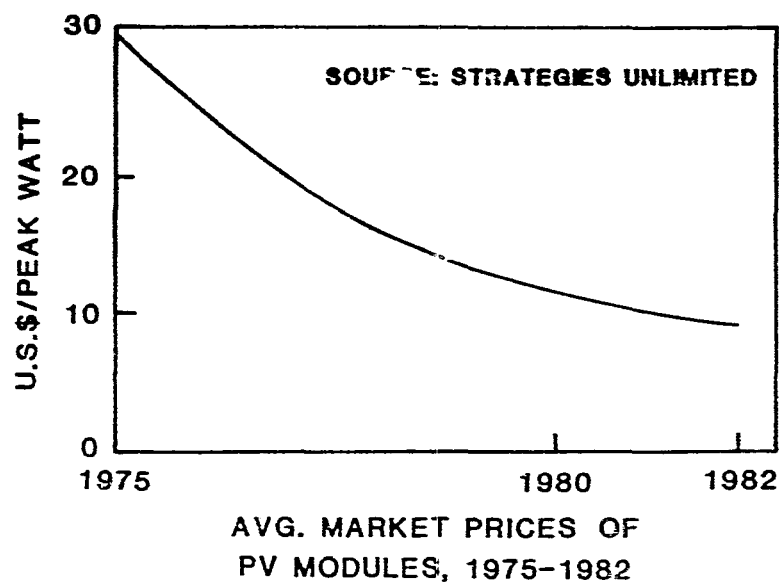
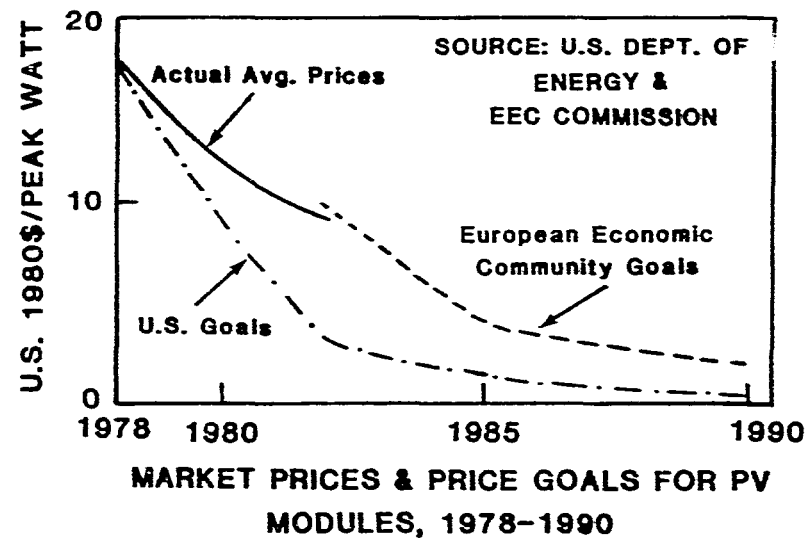
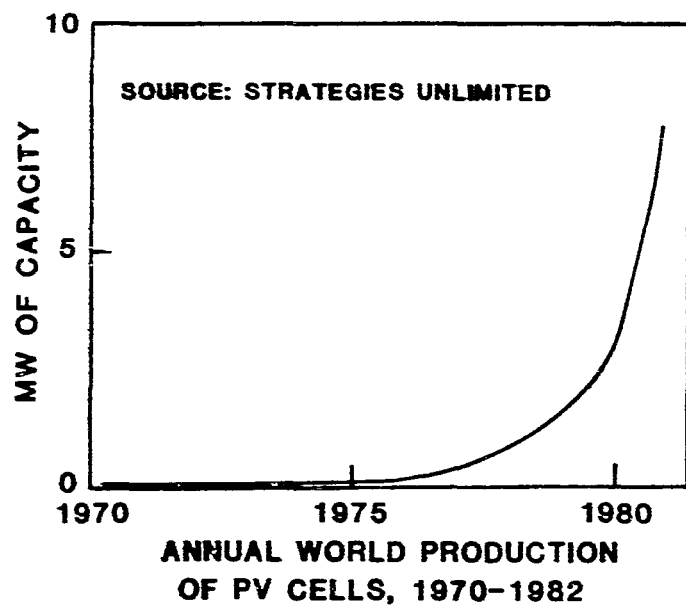


Figure 6-2. RELATIONSHIP BETWEEN CELLS, MODULES, PANELS, AND ARRAYS



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Figure 6-3. PHOTOVOLTAICS UNINSTALLED MODULE PRICE AND WORLD PRODUCTION TRENDS (Source: As Stated)

## Thermoelectric

The phenomena of generation of voltage between the junctions of two dissimilar metals when a temperature difference exists across them, the Seebeck effect, is the basis of operation of thermoelectric systems. This effect is commonly used to measure temperature. The thermocouple, and thermoelectric generators, were first developed as multiple thermocouple arrangements, or "Thermopiles," constructed of dissimilar metal junctions.

Thermoelectric systems technology has undergone some rather radical changes after a very extended period of relative inactivity. Recent advances in the technology have been prompted by both the technology developments in the semiconductor and advanced materials fields and the general increase in energy costs.

Solar thermoelectric generation systems have energy conversion efficiencies in the range of 5% to 8% in hardware demonstrations of solar concentrating systems. This efficiency includes both the solar collector efficiency and thermoelectric generator (TEG) efficiency. When viewed from the standpoint of the solar generation of hydrogen, and the fact that more efficient solar energy conversion processes have been demonstrated, the general conclusion is that these systems are unlikely to see commercial application for hydrogen production in the next two decades. Further, cost of fabrication and materials availability problems must also be considered.

However, thermoelectric generators are commercially available. They find use in gaseous, fossil-fuel-fired TEG's for remote power systems and radio-isotope-fueled systems for space, underwater, and remote power generation. These applications provide the primary impetus to present limited commercialization of this technology.

One disadvantage to this technology is the need to provide active cooling to the low-temperature electrode. No efforts are currently underway toward massive implementation of this technology to solar-driven systems. Cost estimates are in the range of \$5-\$10/watt with an unknown reduction potential. Photovoltaics increasingly enjoy both technical and cost advantages over thermoelectrics.

The Technology Status Ranking is 3--small pilot plant lends support. Due to lack of current activity, this technology is assigned to the post-1992 time-frame. The resource--concentratable insolation--does exist at KSC.

## Thermionic

The following has been excerpted from "Solar/Hydrogen Systems Assessment, Vol. II, Part 1" (Reference 6-7).

"A thermionic converter is a static device which converts heat directly into electricity. It is composed of an emitter, or cathode, which, at one surface, receives thermal energy which raises electron energy level sufficiently to cause the electrons to leave the emitter and travel to the collector, or anode. The anode is usually maintained at a temperature lower than a cathode/emitter by some cooling mechanism.

"Extrapolation of the present status of thermionic technology into the foreseeable future, say, to 1990 and a few decades beyond, indicates that the energy conversion efficiency of thermionic systems will be too low to permit their use as a terrestrial conversion system for solar energy. However, these systems are able to operate at high input temperatures and do reject heat at sufficiently high temperature levels for thermal inputs to heat engines. Thus, thermionic converters can be used as "topping" cycle systems with Brayton, Stirling, or Rankine cycle engines as "bottoming" units.

"It has been made fairly clear that the major problem of thermionic technology is low efficiency, unimpressive output power levels and high operating temperatures, all of which combine to produce high costs per unit power output. Only when the technology improves, to the point where a barrier index of 1.3 eV can be achieved, can thermionics become competitive as a main converter or as a topping device for heat engines in solar concentrator-driven systems.

"Thermionic converters have the advantage of converting heat to electricity directly with no moving parts or working medium in large quantities. Noise and air pollution will not be a problem. Since it has been demonstrated that thermionic converters, either used alone or as a topping device, will not form a more efficient alternative to an advanced heat engine, it is safe to state that thermionic converters will not hold any appreciable advantage in power generation systems prior to the year 2025. All the projections, and related arguments, have been based upon the assumption that no major breakthrough occurs in the technology."

The Technology Status Ranking is 2--laboratory studies leading to an assigned time-frame of beyond 1992. The primary resource--concentratable insolation--potentially exists at KSC.



## Solar Thermal Engines

The use of solar thermal energy to drive a heat engine with subsequent electricity generation is a conversion approach which has received wide attention. Low-temperature, low-efficiency systems may be constructed from components readily purchased in the marketplace (Reference 6-10). High temperature, high-efficiency systems offering the potential of electrical power costs approaching conventional utility power have been designed (Solar 100) and a 10-MW pilot has been constructed and is successfully operating in the U.S. Southwestern desert (Barstow, CA) (Solar One). Four categories of collectors may be considered:

- Solar ponds
- Flat plate
- Distributed concentrating (trough)
- Point focus collectors.

Depending on the collection temperature, these can be coupled to various heat engines:

- Organic Rankine cycle
- Steam Rankine cycle
- Stirling cycle
- Brayton cycle.

Reference 6-7 has a good discussion of these technologies with the exceptions of solar ponds and recent examples of large point focus collectors (power towers). Power Towers are described in References 6-17 and 6-18. Liquid metal magnetohydrodynamic generators, which operate from a collector to produce electricity directly, are covered in the review of electrical generation technologies (to follow).

## Types of Solar Thermal Collectors

### Solar Ponds

The large solar pond is a fairly recent development. The following is excerpted from two recent review articles (References 6-36 and 6-37):

"There are several types of solar collectors referred to as solar ponds; this paper will concentrate on the salt-gradient, non-convecting pond since this is the area where most practical progress is reported to date. Another form of solar pond--known as the saturated solar pond--has been proposed and is described in Appendix I. The term "solar pond" or "shallow solar pond" has been applied to a collector comprising a horizontal plastic bag filled with water; as the theory and technology is predominantly that of conventional flat-plate collectors, the subject is not covered in the present paper.

"The salt-gradient pond is a body of saline water in which the concentration increases with depth, from a very low value at the surface to near saturation at a depth of, usually, 1-2m. This density gradient inhibits free convection with the result that solar radiation reaching the lower region is trapped: temperatures approaching the boiling point of the solution have been recorded."

Good locations for solar ponds are in desert areas near to a source of sea water which can then be evaporated until desired concentrations are reached. The study team contacted Bob Allen of Florida Power & Light Company (FPL) in December 1982, and Dr. Tom Bowman of the Florida Institute of Technology (FIT) in January 1983. Both have studied solar ponds for Florida locations, and Dr. Bowman has recently added ponds as a grant activity sponsored by the State of Florida. A summary of the gist of their comments on the suitability of the KSC environment follows.

The KSC area is characterized by muck pockets and sand dunes. An extensive soil characterization would be needed. The soil has high thermal conductivity due to moisture, with aquifers both deep and shallow. The pond would have to be lined and insulated on the bottom--a costly prospect. The high humidity suggests that evaporation to achieve high salt concentrations will not work effectively. Salt would have to be shipped in and added to the pond. Barge-shipped salt is \$20/ton, trucked salt costs \$35/ton. The high rainfall means that a cover would be needed to keep fresh water from diluting or destabilizing the salt gradient. While thermal gradients have been established, there is no evidence of large-scale extraction of useful heat from a pond without destabilization.

The Technology Status Ranking assigned is 3--supported by a small pilot facility. The time-frame before commercialization is expected to be beyond 1992. While the solar resource needed to supply the energy is present at KSC, the environment is otherwise decidedly hostile such that the pond would be very expensive compared to ponds in desert locations.

### Flat Plate Thermal Collectors

These are readily available from many firms (Reference 6-16) for about \$500 per 32 ft<sup>2</sup> panel, including pumps and installation. They couple quite nicely to organic Rankine cycle engines with or without thermal storage. The solar thermal collection efficiency is about 60%, but output temperatures are low, leading to low system efficiency. Status Ranking is 5--significant commercial experience and a system could be constructed by 1987. The primary resource--direct and global insolation--is available at KSC.

### Distributed Line-Focus Concentrating Collectors ("Troughs")

These are readily available from several firms (Reference 6-16). Several working fluids are utilized with working temperatures up to a few hundred C°, with efficiencies on the order of 65% for tracking collectors. These couple nicely to the low temperature steam Rankine cycle engines or organic cycle Rankine engines. The Technology Status Ranking is 5--significant commercial experience and a system could be constructed by 1987. The primary resource--direct insolation--is available at KSC at approximately two-thirds that of desert or arid regions in the Southwestern United States.

### Distributed Point-Focus Concentrating Thermal Collectors ("Dishes")

The use of tracking parabolic point-focus collectors singly, or ganged in a field, provides for substantially higher temperatures than line-focus systems, but requires more accurate 2-axis orientation means to maintain focused energy on the receiver. Variations on this type of collector involve fixed- or semi-tracked dishes with movable receivers. In some cases, individual heat engines are located directly in the focal-point receiver, e.g., Stirling engine. In others, conventional (but high-temperature) working fluids are transported to and from the receiver. the Technology Status Ranking is 5, with identical comments as above.

### Central Receiver Collectors Using Heliostat Fields ("Power Tower")

Several demonstration plants have shown the viability of this concept, the largest in the U.S. being Solar One at 10-MW (Reference 6-19). A detailed design for a 100-MW plant for the California desert has been completed by Southern California Edison, Bechtel Power Corporation, and McDonnell Douglas Corporation (Reference 6-18). Collection efficiencies are on the order of 60% overall, with coupling to high-temperature steam Rankine cycle engines via thermal storage. The Technology Status Ranking is 4--concept verified by integrated demonstration plant. Construction of such a design is possible by 1987, and certainly by 1992. Some questions remain concerning the appropriateness of the KSC insolation, i.e., transient cloud-cover, high diffuse content.

### Types of Thermal-Collector Operated Heat-Engine

#### Organic Rankine Cycle Engines

These are readily available from several sources, including SPS, Inc., Miami, Florida. Prices are approximately \$1,000/kW for inlet temperatures of

204°F with efficiencies on the order of 7%-8% converting heat to shaftpower. The Technology Status Ranking is 5--significant commercial experience with a few months delivery time. These can be utilized in any low-temperature system at KSC by 1987, e.g., flat-plate collector. Higher temperature systems involve longer lead times and, often, special R&D efforts.

#### Steam Rankine Cycle Engine

The steam Rankine cycle is probably the most widely used approach for stationary heat-to-shaftpower energy conversion engines. Engines are built commercially in sizes from a few horsepower up to several hundred thousand horsepower. In sizes above about 10-MWe (13,400 hp), turbine/generator systems for electrical power generation are well-developed and in utility use up to 1500 MWe. In the smaller sizes, the steam turbine's principal application is for industrial shaftpower, e.g., pumping. These smaller units have, however, been mated to generators for the production of electrical power. In many cases, the small turbine generator match is accomplished via a speed-reducing gear-box.

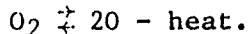
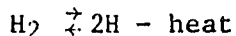
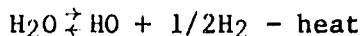
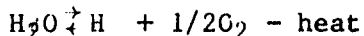
Typical efficiency ranges for a condensing turbine steam Rankine cycle system are shown in Figure 6-4 as a function of inlet temperature. The Technology Status Ranking is 5--significant commercial experience. Individual orders for specialized large systems can take several years to fill. Standard units around 100-MWe can be filled in 1-1/2 to 2 years. Such steam turbine systems can be implemented at KSC by 1987.

#### Other Heat Engine Cycles

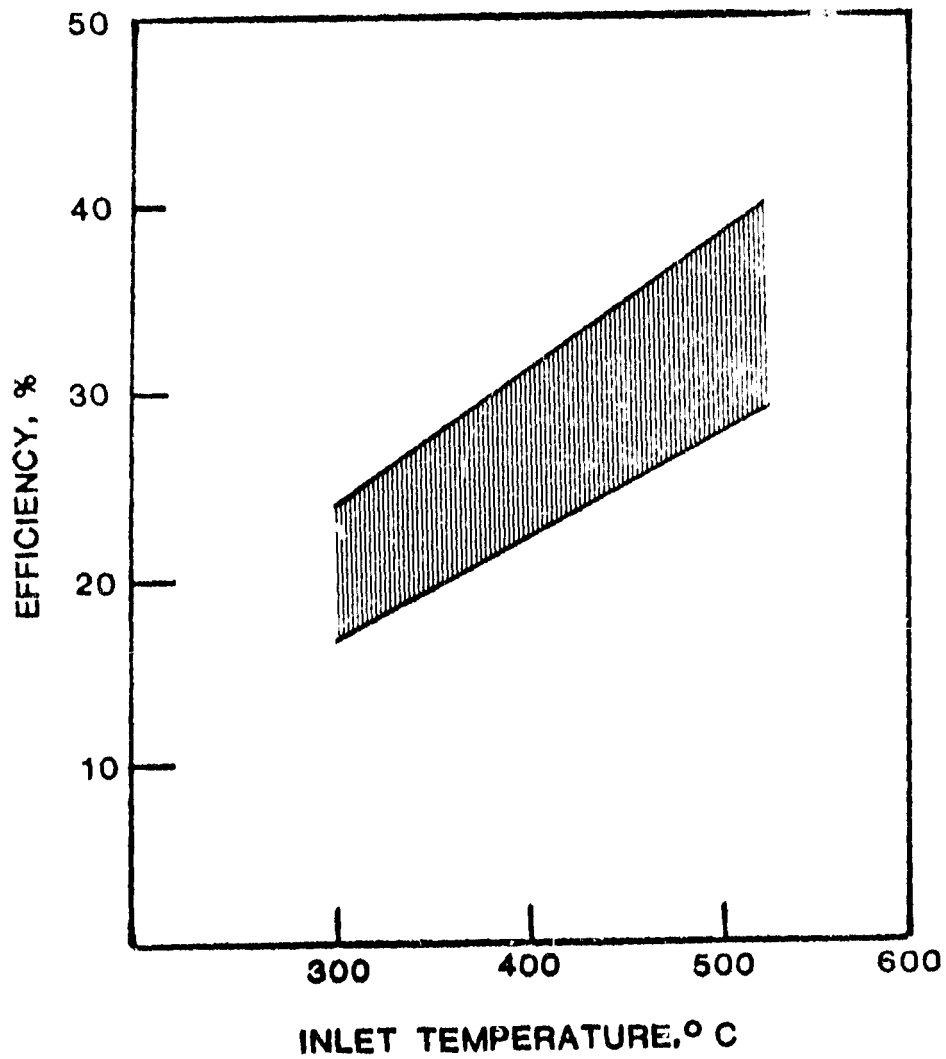
Stirling and Brayton cycle systems offer the promise of higher efficiencies than Rankine cycle systems but very large systems have not been demonstrated for shaftpower generation (Reference 6-7). These systems are assigned Technology Status Ranking 2-3--supported by small pilot and laboratory experience. They are not generally expected to be commercialized for power generation until after 1987, but would be available by 1992.

#### Direct Thermal Water Splitting

If the temperature of water vapor is raised to about 2,000 K or above and its pressure kept low (generally less than 10 atm), the water vapor will partially dissociate in significant quantities. Any energy input will now be absorbed partially by the process of dissociation where the product materials, in equilibrium in fixed volume, will consist of some mixture deriving from the following reactions:



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Figure 6-4. STEAM RANKINE CYCLE EFFICIENCY AS A FUNCTION OF  
TURBINE INLET TEMPERATURE

At this time, laboratory investigation into this process is being done. A recent experiment (Reference 6-20) demonstrated small-scale hydrogen production at 1.1% overall efficiency using steam quenching to cool the hot product gases. The Technology Status Ranking is 2--supported by laboratory studies. Commercialization at large scales is not expected until well beyond 1992 because of the very high temperature requirement, concomitant materials problems, and the large challenge posed by the product separation requirement.

#### Thermochemical Water Splitting

There are two classes of thermochemical cycles: "closed-loop" approaches and "open-loop" approaches. The closed-loop processes are "cycles" in that the intermediate chemical forms resulting from multi-step reactions are recycled back into the loop. Open-loop systems use chemical feedstocks of one type or another which enter the system and are transformed into byproducts of increased value (preferably) while at the same time producing hydrogen and/or oxygen as an output product.

There have been over 200 closed-loop thermochemical water-splitting processes investigated by researchers worldwide (References 6-21 and 6-22). Most of these have been rejected analytically on the basis of one, or a combination of, such factors as probable cost, materials problems, temperature and/or pressure demands, reaction rates and equilibrium points, net energy efficiency, etc. Most of the early work done in the field considered the use of nuclear fission energy as the primary energy source. More recently, investigations of the use of solar energy and thermonuclear fusion energy as the primary energy source have been undertaken. If materials engineering problems can be overcome, solar-driven, closed-loop thermochemical systems may well operate well above the 1,000°C to 1,200°C limits of advanced nuclear fission. This could add considerable flexibility to the chemistry of thermochemical cycles, although no cycle has yet been demonstrated to take advantage of such temperatures. However, continued steady-state process operation is a major challenge. Any steady-state solar operation requirements denotes the need for cost-effective, very high temperature thermal energy storage systems, a technically difficult area.

There is no current technology of significance for solar-driven, open-loop thermochemical cycles.

The Technology Status Ranking is 2--supported by laboratory studies; with an earliest time of commercial implementation of well beyond 1992.

#### Hybrid Electrolytic-Thermochemical Cycles

The objective of hybrid electrolytic-thermochemical water-splitting cycles is the same as that of basic closed- and open-loop thermochemical cycles, i.e., the production of hydrogen more efficiently than can be achieved with entirely electrically driven processes.

In a number of possible thermochemical hydrogen production processes, a key reaction cannot be thermally driven. Indeed, the addition of heat to that particular reaction step can produce exactly the opposite effect desired. In those instances where such a reaction step is encountered, the opportunity may exist to substitute an electrically-driven electrolysis reaction, thus enabling the balance of the reactions needed to close the cycle to proceed.

Such systems that combine thermal energy input to various reaction steps with an electrically-driven step or steps are referred to as "hybrid" thermochemical cycles.

Present research is aimed at the development of the process chemistry and equipment designs based upon thermal energy and electrical energy sources other than solar. The focus of present investigations is on basic chemical engineering and materials problems, including basic process chemistry validations. Pending success in these endeavors, the technical and economic characteristics of this class of processes will remain undefined.

The Technology Status Ranking is 2--supported by laboratory studies; with a time of commercial implementation of beyond 1992.

#### Wind Energy Conversion Systems

A comprehensive discussion of this process is covered in Reference 6-2. As noted in Section 4 of this document, the nearest acceptable wind resource for such systems is 100 to 200 miles northeast of KSC. While "wind farms" have been developed in certain mountain and western states in the U.S., no significant offshore-based technology has been demonstrated. Due to this, and the lack of a local resource, this technology is dropped from further consideration.

#### Ocean Thermal Energy Systems (OTEC)

##### General Discussion of Process and Status

An excellent review approaches to utilize thermal gradients in the ocean as heat sources and sinks is found in Reference 6-2. To review the current status of OTEC, the study team contacted two researchers in this field. With closed-cycle systems being well-documented, the inquiry focused on the less-developed open-cycle approach.

Dr. Tomlinson Fort, California Polytechnic State University (formerly Carnegie-Mellon University, Colleague of Drs. Zener and Lavi). Dr. Fort has been a prominent researcher and author in this field, working with his colleagues at C-M, and a telephone contact was made with him at his new position at Cal Poly (he is a University Vice President).

Dr. Abraham Lavi, Consultant (formerly Carnegie-Mellon University, Colleague of Drs. Zener and Fort). Dr. Lavi noted that he had gravitated in recent years from the technical side to the financial side of OTEC. Specifically, he was now working with Ocean Thermal Corporation (a subsidiary of Basic Resources, Inc., New York). A summary of the discussions follows.

Open-cycle OTEC provides two noted advantages over the closed-cycle approach: (1) both heat exchangers are eliminated and (2) fresh, or at least lower salinity water is provided as a byproduct. The former advantage leads to reducing hardware costs while increasing somewhat the working  $T$ , and also eliminating the potential heat exchanger biofouling problem.

There are a number of variants on the open-cycle theme, but basically the difference in vapor pressure between the warm surface water and the cold depth water is used to lift water in one form or another, increasing its

potential energy, which is subsequently converted to shaftpower and electricity (and on to hydrogen). The variant selected by the C-M research team is "foam OTEC" in which the rising water column is in the form of a soap-suds like foam.

Returning to closed-cycle systems, Dr. Lavi reviewed the situation noting the following:

- Cold-water pipe has emerged as the high cost item (formerly perceived to be heat exchangers).
- Based largely on existing industrial practice (e.g., tube in-shell heat exchangers), none of the "show stoppers" such as biofouling have panned out, i.e., OTEC is imminently doable in his view.
- The "market-entry price" of power from an OTEC plant is believed to be in the range of 90 mills/kWh (well above conventional alternatives).

#### Federal Government OTEC Support and Perceived Position

Following a substantial budget funding situation over many years, the Federal Government support for OTEC (via NSF, ERDA, and DOE in that progression) has now been sharply reduced. The FY'84 budget request is for only about \$10 million. This is in sharp contrast with earlier years, e.g., FY'81 funding of about \$34 million. To the best of the study team's understanding from the technical literature, direct conversations with DOE personnel, and researchers in this field, the "official position" of the Government is that OTEC is now at the commercialization-entry stage. This is reflected in the strongly reduced DOE funding level in an aura emphasizing "high-risk, long-term" research. Included are 40-MWe prototype facility conceptual design studies by General Electric Company and by Ocean Thermal Corporation at about \$1 million apiece. Significantly, both address shore/bottom-mounted facilities off Hawaii. One is "topped" by effluent from several fossil-fueled utility plants.

#### OTEC Cable Ashore Plus Overland Wheeling

As reviewed earlier, "workable" OTEC conditions of differential temperatures of 20 C (minimum) are available off the Eastern coast (say, 100 miles) of Florida for only part of the year, e.g., April-November. Year-round resources are limited to the waters between Key West and Cuba, and possibly locations in the Gulf of Mexico (but well off Florida's West Coast). To utilize OTEC-power for an onshore electrolyzer-grid facility for hydrogen production and liquefaction at KSC would thus require:

1. DC cable from OTEC facility to shore
2. AC power local-wheeling to KSC through FPL's system, and possibly other Florida utilities (difficult to assess cost-wise).

#### OTEC: Liquid Hydrogen On-Platform Production

Another alternative would be to produce liquid hydrogen directly on the OTEC platform and ship or barge the product to KSC. Locations for the OTEC operation would thus be opened to sites at much greater distances from KSC



(than underwater cable delivery). Johns Hopkins University's Applied Physics Laboratory has focused on such production of physical energy products, e.g., ammonia, liquid methane, methanol, liquid hydrogen.

Their estimates for the price of liquid hydrogen ashore seems quite competitive. However, E:F's contacts with researchers in the OTEC field (e.g., Dr. Lavi) strongly suggest that JHU/APL may be sharply optimistic regarding product costs.

#### Summary of Findings

1. On the one hand, Federal Government is perceived to take the position that OTEC is now at the commercialization-entry stage, i.e., awaiting entry of industrial gas firms, et al., in the case of OTEC/LH<sub>2</sub>. Thus, further R&D funding for OTEC will thus likely be small, particularly in the case of the present administration.
2. On the other hand, lack of any evident commercialization initiatives by U.S. industry to date would seem to signify that there will be a multi-year "lull" period at best; it follows that a mature-technology ca. 20-MW<sub>e</sub> plant (capable of meeting the KSC LH<sub>2</sub> production requirement) will fall significantly later than the 1987 initial date of interest.
3. Near-Florida basing of OTEC is not particularly favorable in comparison with Hawaii, et al., and equatorial zone locations, e.g., off Brazil in the Atlantic. Hence, far-remote (from KSC) OTEC siting is indicated.
4. Finally, with detailed design and costing analyses of alternative OTEC facilities having been already documented at study costs far greater than the value of the present contract, little new could be contributed by the present study team in new-start assessments of the OTEC alternative.

The Technology Status Ranking is 3--concept supported by small pilot facility. The earliest possible time for implementation (following at least two commercial plants) is seen to be the 1992 time period.

#### Other Indirect Solar Energy Conversion Systems

##### Wave Systems

A good discussion of this technology can be found in Reference 6-7. Section 4 of this document showed that an adequate resource is not available within 1,000 miles of KSC. This, taken together with the lack of commercially-available equipment, lead to dropping this technology from further consideration.

##### Hydropower

At or near KSC no resource exists. The technology is, however, well established. Use of this resource and technology is equivalent to purchasing and transporting electrical power or liquid hydrogen product. The technology itself is not of concern nor is it discussed further in this document.

## Biological

The production of fuels, or energy carriers, from biomass and wastes has been extensively studied. Many demonstration and commercial systems are now operating in the United States, with others planned (Reference 6-38). The principle products from these systems are hydrocarbon fuels, including partially-oxygenated products, e.g., alcohols. These hydrocarbon fuels, for the most part, are readily usable in present-day, fuel-using equipment. Processing to hydrogen requires an energy investment which cannot be returned and it yields a less desirable fuel in terms of energy content and storability.

Given a future in which hydrogen is a preferred energy carrier, the reforming of biologically produced hydrocarbons may be desirable in order to produce a fuel compatible with the deployed system. However, even then it is probable that these hydrocarbons will be of more value as industrial feedstocks and thus will be retained for this market.

On the other hand, it appears that the direct combustion of biomass and wastes in more or less conventional equipment, producing electricity (e.g., via steam turbines) and thence hydrogen via electrolysis is the more likely candidate for the production of hydrogen from biomass and wastes. However, if the fuel for this process is municipal refuse with plant siting near an urban area, electricity may be the preferred energy carrier for delivery. In any event, such electricity is likely to cost more than the conventional fossil-fueled baseload equivalent.

Given these prospects for biomass and waste utilization, biological techniques as indirect solar energy conversion technologies are not treated further in this report.

Biophotolytic systems are not based upon the conversion of biomass to other fuel forms. Hydrogen is produced as a product of growth and maintenance of a unique biological system.

Biomass waste from biophotolytic systems might be subsequently converted by biomass conversion techniques, but the basic fuel form arguments presented above would still apply to such uses.

## Categories of Electrical Generation Systems (for Water Electrolysis)

Where the output of the energy conversion technologies is shaftpower, as in the case of wind-power, heat-engine systems, etc., electrical generation capability is required to interface the energy conversion technologies with water electrolysis equipment to provide hydrogen product output. In these cases, four categories of generator designs are available: conventional AC and DC, and unconventional DC rotating machines, and magnetohydrodynamic generators.

### Conventional AC Generators

AC rotating-machine generators have been deployed for many years over a very wide range of sizes. Efficiencies are quite high in the MWe-class systems and the technology is state-of-the-art. However, since water electrolyzers require DC power, hence costly transformer/rectifier units are needed.

### AC Generator Systems

In the smaller size range, the recent development of compact, inexpensive, high-power, solid-state rectifier equipment has provided significant improvement in AC generator technology. These integral alternator-rectifier designs provide less expensive, more reliable sources of DC power and their efficiency over the rotating speed range of the AC systems is superior to the conventional DC generator in many applications. The rectified alternator is the leading contender, among those of conventional design, for matching some shaftpower output of energy conversion technologies to electrolysis systems, namely low-power units.

### Conventional DC Generators

Electrolysis systems require DC power input with the input voltage varying considerably from relatively low voltages up to 1,000 volts. The conventional DC generator design is the familiar brush-type, commutator-equipped machine. Several limitations in the conventional DC generator design must be considered, e.g., they are not usually as efficient as AC equivalent designs. Large DC machines--up to several thousand KW--may have efficiencies of about 90%-95%. AC alternators in this class may operate at 95%-97% efficiency with larger, hydrogen-cooled units in the 25-MWe range achieving about 98% efficiency. DC generators are not widely available beyond the 5-MWe size (Reference 6-23).

The requirement for a commutator-brush system in conventional DC generators leads to maintenance problems and attendant costs, e.g., periodic brush replacement and resurfacing of the commutators. DC machines are typically heavier and provide no particular capital cost advantage over their AC counterparts.

Generally, the requirements for generating equipment to drive electrolysis systems are not the same as the requirements for systems that would provide grid power. There is no need for exact voltage control or frequency synchronization. Since an electrolysis cell can operate over a wide range of input currents, the operating speed of rectified alternator systems, and DC generation equipment also, can be allowed to vary with the input

power. This capability is advantageous in this particular type of system under study here. This type of use could be considered an "unconventional" use of conventional generating equipment.

#### Unconventional DC Generation (The Acyclic Generator)

A potentially attractive type of unconventional DC machine is the acyclic unipolar, or homopolar generator. The acyclic generator is a low voltage, high-current device well-suited in the first analysis to interfacing with water electrolysis equipment. It operates on the "Faraday Disk" principal, and has efficiency and cost characteristics similar to those of a conventional MWe class alternator, while being physically much simpler than conventional units. Its compact rotor being typically a single piece of machined steel which does not use copper conductors. The largest acyclic generators known are 4.5-MWe machines, four in number, located at the Air Force's Arnold Engineering Developmental Center near Tullahoma, Tennessee.

A preliminary assessment of the acyclic generator for powering water electrolyzers was carried out by the Institute of Gas Technology's (IGT) in 1975 (Reference 6-24). On the basis of hydrogen production costs, the use of acyclic generators proved rather favorable under the conditions of the analysis. The subject of study was a dedicated, advanced-technology, nuclear, electrolytic hydrogen production facility.

#### Low-Temperature Liquid-Metal MHD Power Systems (References 6-25 through 6-29 and Appendix A)

Emphasis in magnetohydrodynamic (MHD) systems to date has been on plasma-based systems requiring the very high temperatures usually associated with fossil-fuel combustion. An alternative approach is to utilize two working fluids--one a compressible thermodynamic fluid; the other an electrodynamic fluid (e.g., a liquid metal)--to obviate the need to create plasma working fluid.

This approach opens the door for efficient, low-temperature DC electricity generation compatible with a range of thermal energy sources. Technical articles have been presented since 1980 by Argonne National Laboratory (ANL) (Reference 6-26), NASA-Langley (Reference 6-27), and Technology (Reference 6-28) describing this approach. Low-temperature MHD appears to be an attractive candidate for DC power production. Initial studies suggest electricity costs 2 to 10 times lower than conventional solar-thermal and photovoltaic systems.

Comparison of Solar Electric Net Costs	(\$/kWh)
Solar Liquid Metal, 2-Phase MHD System	.054
Solar Organic Rankine Cycle System	.116
Solar Photovoltaic System	.570

Source: Reference 6-28

Referring to Figure 6-5, the liquid metal constituent is heated in the solar collector and goes to thermal storage (or directly to the mixer). In the mixer, it is mixed with cold, dense (compressed) gas. The heated gas and liquid metal expand as a 2-phase mixture and are accelerated through the MHD-generation section producing DC power.

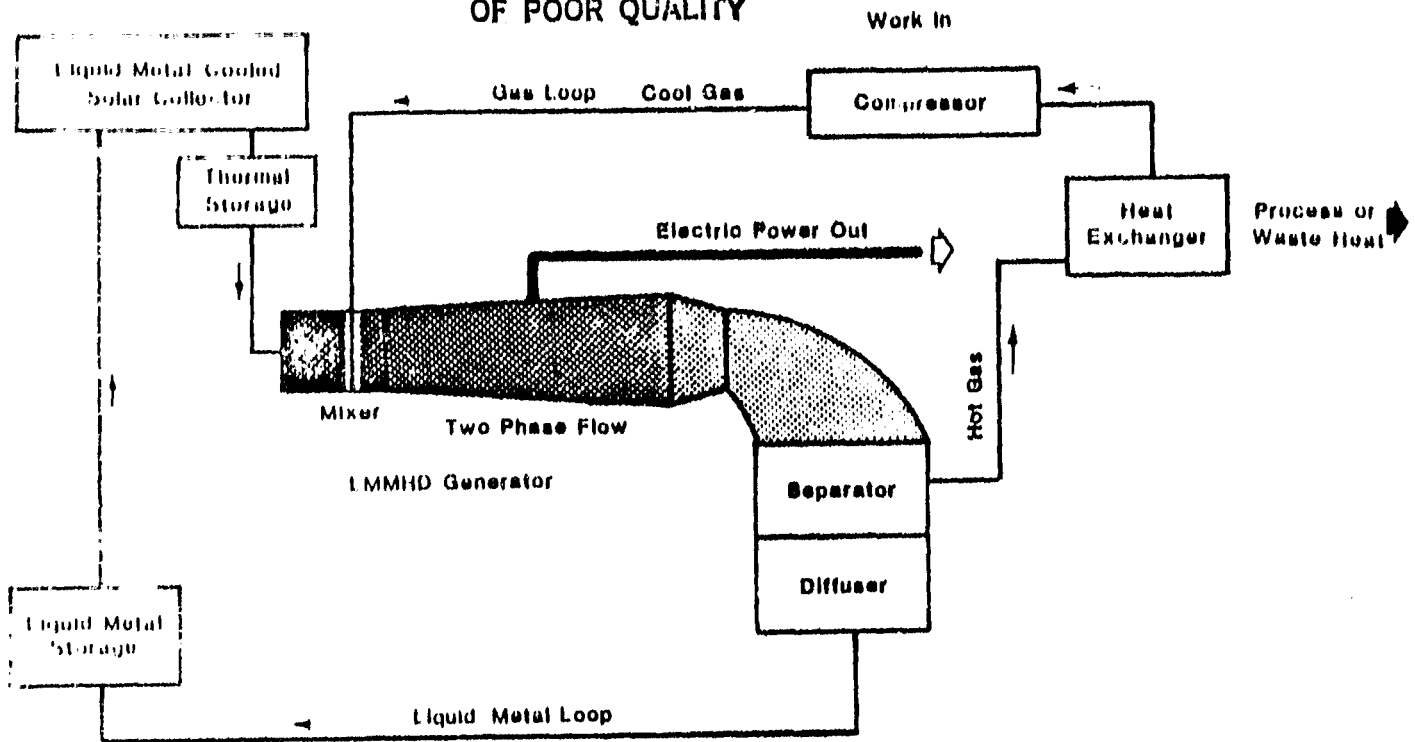


Figure 6-5. SIMPLIFIED SCHEMATIC DIAGRAM OF A REPRESENTATIVE LIQUID METAL-OPERATED MAGNETOHYDRODYNAMIC SYSTEM

Once decelerated in the separator/diffuser, the hot gas and liquid metal return separately in their respective flow loops. The gas is cooled in external-media heat exchangers which poses an opportunity for cogeneration heat recovery. The liquid metal, cooled in heating the gas, returns to storage and then is pumped back to the solar collector. As suggested by the ANL investigators (Reference 6-26), the system can be considerably simplified by using an organic working fluid which would provide a pumpable liquid and a compact mixer. It is suggested that an electromagnet pump be used to simplify the liquid metal loop. The study team also emphasizes the potential of cogeneration in this system.

In summary, this innovative and relatively recent development appears to be a candidate energy conversion means for thermal energy conversion (solar, nuclear) to DC power output for interfacing with water electrolyzer systems. A further review of the technology and its applicability to systems of concern here is contained in Appendix D, prepared by Dr. Lee, a special consultant on the study team.

#### Electrical Generation Technology Status and Timing Recap

While electrolyzer needs are DC, large machines producing DC power are not widely available beyond the 5-MWe size, implying the need for parallel units. Conventional AC may be rectified to provide the needed DC. With the exception of low-temperature liquid-metal MHD generators, a technology Status Ranking of 5--supported by significant commercial experience--may be assigned, with a 1987 time-scale easily realizable. The low-temperature liquid-metal MHD generator, whether used as a topping cycle or in stand-alone applications, is assigned a Technology Status Ranking of 2--supported by laboratory studies. It has a time-scale of beyond 1992.

## Electrolyzer Design Categories and Related Considerations

Three basic water electrolysis technologies and configurations were considered in this study. These design alternatives are broadly competitive over a range of power costs, with each optimizing at a different current density. The three design categories are:

### Unipolar (Tank) Electrolyzer (Alkaline Electrolyte)

The Unipolar (Tank) Electrolyzer has its active electrolytic components supported in an open container (tank) of electrolyte. Electrodes of the same polarity are connected to form cells with about 2.0-V applied across it to provide the relatively high current flow. Individual tank units are connected in series or in parallel as modules.

The tank-type unit usually costs less to construct than the filter-press unit (discussed below), and optimizes in a capital cost/trade-off at somewhat lower current density levels than does the structurally more sophisticated, higher-cost, filter-press system. In the tank-type unit, individual cells can be isolated for maintenance and repair, which is not usually the case for the filter-press configuration.

### Bipolar (Filter-Press) Electrolyzer (Alkaline Electrolyte)

This design configuration is used by the majority of the manufacturers of such equipment. The filter-press (or bipolar) electrolyzer consists of a stack of alternating electrodes, separators, and various gaskets and adjunct items, forming a compact "stack" of cells electrically connected in series. For a typical cell stack, the applied voltage is the sum of the individual cell voltages (each is about 2.0-V, or slightly lower). The resulting voltage requirement can be in the range of several hundred volts, at a correspondingly lower current rating as compared with tank-type unit installations. Each electrode has an anode and a cathode face at opposite polarities, hence the descriptor "bipolar." Filter-press electrolyzers are typically more compact than tank-type units and are more amenable to electrolysis at elevated pressure. However, unlike tank-type units, if a cell failure occurs, the entire stack must be shut down for repair. Filter-press electrolyzers usually present high capital costs per unit of active area (electrode) and accordingly, they tend to be operated at higher current densities. This tends to reduce the efficiency advantages. Substantially more in the way of ancillary equipment is needed (vs. unipolar designs).

### Solid Polymer Electrolyte (SPE) Electrolyzers (Acid Electrolyte)

Usually configured in the filter-press, or bipolar, layout, SPE designs use a separator material which provides for ion exchange directly within the solid material rather than in a liquid electrolyte. Only water is circulated within the cell. Technically, the SPE is classified as an acid electrolyte system. The electrode is either integrally imbedded in the surface of the ion exchange material (which acts as a separator), or takes the form of separate sheets of metal sandwiched between the SPE material. The advantages of this design are as follows:

- A very thin sheet of electrolyte can be used, allowing for low cell resistance and compact cell stacks.

- The electrolyte is entirely captive and cannot be lost from the cell by carry-through or leakage; water only is contained as a liquid
- Very high current densities can be used, which allow for minimizing the amount of SPE and other cell materials required, thus reducing costs.

It should be noted that such design features are not necessarily exclusive to the SPE system. Similarly thin membranes can be used with equal benefit in conventional unipolar and bipolar electrolyzer designs (Reference 6-30).

### High-Temperature Electrolysis of Water

One avenue for improving the effectiveness of water electrolysis is by increasing the operating temperature of the electrolyzer system. The basic rationale for high-temperature electrolysis is to provide a means to substantially reduce the amount of electricity required for the water-splitting process. Heat energy is substituted for electrical energy as stipulated by the Gibb's Free Energy Requirement. By this shift, the heat-to-electricity conversion losses encountered in generating the electrical feed to the system are reduced and the overall electrolysis process is performed at higher efficiency. The Carnot efficiency losses in electricity generation are not encountered in direct heat addition.

In high-temperature electrolysis (nominally 800°C and higher), quite different construction technologies than those used in conventional electrolysis systems previously discussed are clearly required. The following general advantages are stated for this approach (Reference 6-31):

- The electrical energy requirement for the electrolytic decomposition reaction decreases with increasing temperature, leading to an increasing opportunity for the direct utilization of heat.
- Current densities can be significantly higher than at ambient temperatures because of improved reaction kinetics and consequently lower polarization losses are experienced.
- The amount of heat needed for the endothermic electrolysis reaction can be supplied by internal resistivity losses of the electrolysis cell itself or by direct heat input from a high-temperature heat source, or both.
- The total energy requirement for the electrolytic process is lower in the vapor phase and the energy for evaporation may be provided by heat instead of "more precious" electrical energy.

The net benefits are stated to be:

- A reduction in required electrical energy and, hence, primary energy and associated capital and operating costs
- Possible reduction in electrolysis capital costs through the use of higher current densities in the electrolyzer.

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### Technology Status Recap

Water electrolyzer technology, with the exception of high-temperature units, is mature while being further improved with efficiencies of up to 80% achievable, at costs in large quantities expected to be as low as \$200/kW (References 6-32 and 6-33). Accordingly, a time-scale of 1987, with a Technology Status Ranking of 3--significant commercial experience--is assigned. For the high-temperature process, a Technology Status Ranking of 2 is given--supported by laboratory studies. This technology is hence rated "beyond 1992."

### Categories of Liquefaction Systems

#### "Conventional" Systems

In order to place the most appropriate liquefaction system option in perspective, the logic leading to this single selection should be placed in context with other alternatives. There are three basic types of conventional liquefaction system design approaches which are selected primarily as a function of the scale of production. These are:

- The simple Joule-Thomson Cycle
- The complex Joule-Thomson Cycle
- Low-Pressure Expander Cycle.

The simple Joule-Thomson cycle system involves the precooling of hydrogen feed and recycled refrigerant heat-exchanged against liquid nitrogen followed by a Joule-Thomson expansion, which forms the liquid hydrogen product. The efficiency of this cycle depends mainly upon the liquid nitrogen temperature level, which is reduced below normal atmospheric boiling point by means of a vacuum pump. Two stages of ortho-para hydrogen conversion may be provided in this cycle--one at the liquid nitrogen temperature level and one at the liquid hydrogen final/stage temperature level (Reference 6-34).

The complex Joule-Thomson cycle system is appropriate to greater production capacity situations and is designed for reduced power consumption by precooling the hydrogen against atmospheric as well as vacuum boiling nitrogen in a staged manner. Additional savings may be realized through a double Joule-Thomson flash of the hydrogen. The ortho-para conversion of the hydrogen may be accomplished at 2 to 4 temperature levels, which increases the thermodynamic reversibility of the process reducing energy requirements (Reference 6-34).

The low-pressure expander cycle precools the hydrogen with cold gaseous nitrogen and boiling liquid nitrogen. The boiling liquid nitrogen may be considerably above atmospheric pressure, at atmospheric pressure, or under vacuum, depending upon optimization determinations. Below the nitrogen precooling level, additional refrigeration input is provided by means of an expansion engine. The expander may be a reciprocating or centrifugal machine, depending upon size and the operating pressure level selected for the cycle. Below the expander level, the refrigeration input is normally by means of Joule-Thomson expansion in two stages. The expander cycle may take advantage of staged conversion to increase cycle efficiency to a greater extent than for the simple or complex Joule-Thomson cycles (Reference 6-34).



Table 6-1 presents the power requirements for liquid hydrogen production in these three basic cycle systems. It is important to note that the production rate of the KSC Non-Fossil Hydrogen Production System falls in the range of production rate appropriate to the use of low-pressure expander cycles.

Table 6-1. POWER REQUIREMENTS FOR LIQUID HYDROGEN PRODUCTION

Process	Kilowatt-Hrs of Power per Pound of Liquid Hydrogen	Approximate Range of Production Pounds per Day	Pounds Liquid Nitrogen Refrigeration per Pound Liquid Hydrogen
Joule Thomson cycle--simple	10	0- 4,000	11.6
Joule Thomson cycle--complex	8.7	4,000- 10,000	10.0
Expander Cycle	5.0*	6,000-120,000	

\* Includes power for nitrogen liquid and cold gas refrigeration.

Source: Newton, Charles L., Hydrogen Production, Liquefaction and Use, Cryogenic Engineering News, August 1967.

The situation is even more clearly illustrated in Figure 6-6 which presents the carnot efficiency of oxygen liquefaction equipment as a function of system size. This same characteristic shown is found in hydrogen liquefaction systems also. This curve should clearly illustrate the desirability of selecting the maximum practical economic module size for a given production requirement. In the situation under study here, this production requirement is of sufficient volume, on a daily basis, to support the construction of equipment using conventional technologies which will operate at or near the best efficiency obtainable.

Conventional liquefaction has a Technology Status Ranking of 5--supported by extensive commercial experience--and thus a time-scale of 1987. Details on costs, power requirements, and plant size are presented in Section 9 of this document under Finalist Systems Analysis.

#### "Unconventional" Liquefaction Equipment

The principal sources of the inefficiencies in conventional liquefaction systems are in the compressor systems, cooling heat exchange systems, and gas expanders. It is generally agreed that the maximum efficiency of these conventional designs is about 35%-40% of carnot efficiency. It is highly unlikely that any significant improvement in these performances will be achieved with these basic technologies. The only presently-known alternative to these present technologies is found in systems based on the

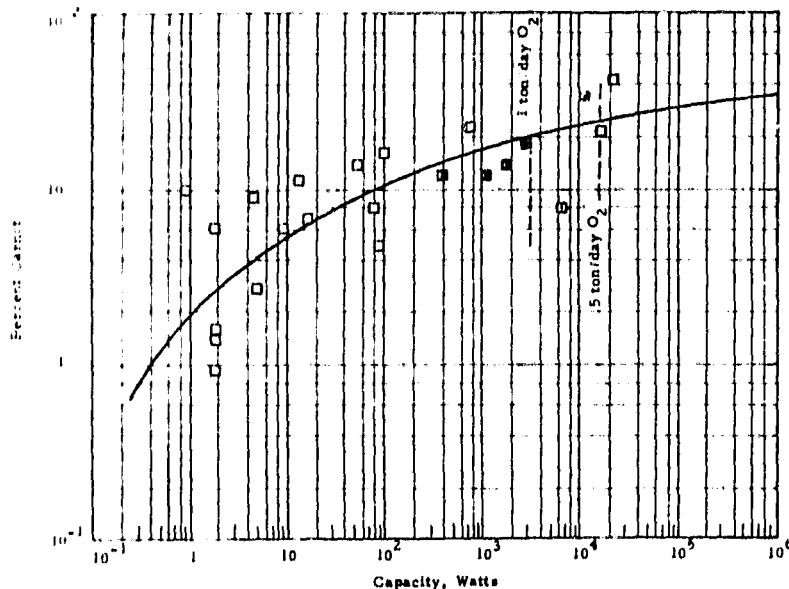


Figure 6-6. CARNOT EFFICIENCY OF OXYGEN LIQUEFACTION EQUIPMENT AS A FUNCTION OF SYSTEM CAPACITY

(Source: Parrish, W.R., et al., "Selected Topics on Hydrogen Fuel," NBSIR 75-803, National Bureau of Standards, U.S. Department of Commerce, Boulder, CO, January 1975)

"magnetocaloric" effect or Magnetic Refrigerators. These refrigerators exploit the temperature and magnetic field dependence of the magnetic entropy of a solid material to extract heat from a low-temperature source and transfer it to a higher temperature sink. Work on these systems is presently underway at the Los Alamos National Laboratory.

While this category of liquefaction equipment is only in the research stage, the potential capabilities of this technology--as it might become operational--are worthy of discussion. Dr. John Barclay notes for a 20-W, 4-stage Magnetocaloric Liquefier:

"Although a comparison with existing gas refrigerators is somewhat unfair because no 20°K-300°K magnetic liquefier has been built, it is interesting to compare to see what potential advantages are projected by analysis...We see that this magnetic liquefier potentially offers a factor of approximately 7 increase in efficiency, a factor of greater than 10 decrease in equipment volume, and a factor of greater than 3 decrease in mass, all at very low operating speeds which should enhance reliability." (Reference 6-35.)

This promising technology is reviewed more fully in Appendix B. It is assigned a time-frame of beyond 1992, with a Technology Status Ranking of 2--supported by laboratory studies.

### Summary of Technology and Resource-Availability Screening Results

A summary of the technology and resource-availability screening is shown in Table 6-2, which displays technology status, estimated timing, and resource availability. For either the 1987 or 1992 target year, the building blocks for the KSC liquid hydrogen system always involve the production of electricity followed by water electrolysis and conventional liquefaction. By 1987, only photovoltaic and solar-thermal engine-generator systems are available to produce electricity. By 1992, it may be possible to invoke a modular fission reactor/thermal engine generator system as well. For OTEC systems, provided either the electricity or liquid product can be transmitted or shipped to KSC, the earliest time seen for the system is about 1992. The remaining candidates are generally considered in the "beyond 2000" category.

Table 6-2. SUMMARY OF TECHNOLOGY AND RESOURCE-AVAILABILITY SCREENING

TECHNOLOGIES	TECHNOLOGY STATUS RANKING	EARLIEST TIME FRAME
Non-Fossil Primary Energy Resources		
Nuclear Energy		
Fission Burner Reactor (Modular Unit)	5	1992
Fission Breeder Reactor	2	>1999
Fusion Systems	2	>1999
Geothermal Energy	4	1987
Non-Fossil Primary Energy Conversion Technologies		
Direct		
Photic		
Biophotolysis	2	>1992
Photocatalysis	2	>1992
Photoelectrocatalysis	2	>1992
Electric		
Photovoltaic	5	1987
Thermoelectric	2-3	>1992
Thermionic	2	>1992
Thermal		
Thermal Engines	5	1987
Direct Thermal Water Splitting	2	>1992
Thermochemical Water Splitting	2	>1992
Hybrid Electrolytic-Thermochemical Water Splitting	2	>1992
Indirect		
Mechanical		
Wind Energy Conversion Systems (WECS)		
Ocean Thermal Energy Conversion Systems (OTEC)	3	1992
Wave Systems	2	?
Hydropower	5	1987
Biological	4	1987
Hydrogen Energy Production Technologies		
Electrical Generation		
DC Machines	5	1987
AC Machines	5	1987
Homopolar Machines	5	1987
Magnetohydrodynamic Machines	2	>1992
Electrolysis Systems		
Unipolar Tank Electrolyzer	5	1987
Bipolar Filter-Press Electrolyzer	5	1987
Solid Polymer Electrolyzer	5	1987
High-Temperature Electrolyzer	2	>1992
Hydrogen Liquefaction Technologies		
Joule-Thomson Expander Technology	5	1987
Magnetocaloric Refrigeration Technology	2	>1992

# D RESOURCE-AVAILABILITY SCREENING

TECHNOLOGY STATUS RANKING	EARLIEST TIME FRAME	KSC RESOURCE AVAILABLE	INITIAL OPERATING CAPABILITY		
			BY 1987	AT KSC BY 1992	BEYOND 1992
5	1992	N.A.		X-----	
2	>1999	N.A.			X
2	>1999	N.A.			X
4	1987	No			
2	>1992	Yes			X
2	>1992	Yes			X
2	>1992	Yes			X
5	1987	Yes	X-----		
2-3	>1992	Yes			X
2	>1992	Yes			X
5	1987	Yes	X-----		
2	>1992	Yes			X
2	>1992	Yes			X
2	>1992	Yes			X
3	1992	No			
2	?	No		(X)-----	
5	1987	No			
4	1987	No			
5	1987	N.A.	X-----		
5	1987	N.A.	X-----		
5	1987	N.A.	X-----		
2	>1992	N.A.			X
5	1987	N.A.	X-----		
5	1987	N.A.	X-----		
5	1987	N.A.	X-----		
2	>1992	N.A.			X
5	1987	N.A.	X-----		
2	>1992	N.A.			X

2 FOLDOUT FRAME

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## 7. CANDIDATE SYSTEMS CONCEPTUAL LEVEL DEFINITION AND SCREENING

From a KSC-needs standpoint, an approximate time-scale for early implementation of a large-scale, non-fossil, liquid hydrogen production system, as discussed earlier, is 1987-1992. While the specific technologies involved would be a function of the specific date selected, 4 to 5 years would be a reasonable estimate of project go-ahead to Initial Operating Capability (IOC).

This implies that for a 1987 implementation, the constituent technologies would have to be commercially available today, whereas for a 1992 implementation, the equipment would have to be available or expected to be available within the next five years, i.e., by 1988.

The second-level screening of system candidates will be largely an economic screening, implying that sufficient information about the involved technologies are available to permit reasonable cost projections to be made. This fact limits system choices to be considered to be made up of technologies which have advanced past the small pilot-plant stage of development to permit reasonable approximations to be made. The first-screening results (Section 6) thus limit the systems to be further considered to include: solar thermal engine systems, photovoltaic systems, nuclear systems, and remote shipped product systems (e.g., via OTEC). The technical building blocks for these systems are shown in Figure 7-1.

For the purposes of this comparative economic screening step, the downstream liquid hydrogen storage and delivery subsystems which are common to all systems are assumed to be in place and are explicitly not included in the screening calculations. Each system is evaluated using the Electric Power Research Institute's (EPRI) Technical Assessment Guide (TAG) model (Reference 7-1) using identical assumptions as follows:

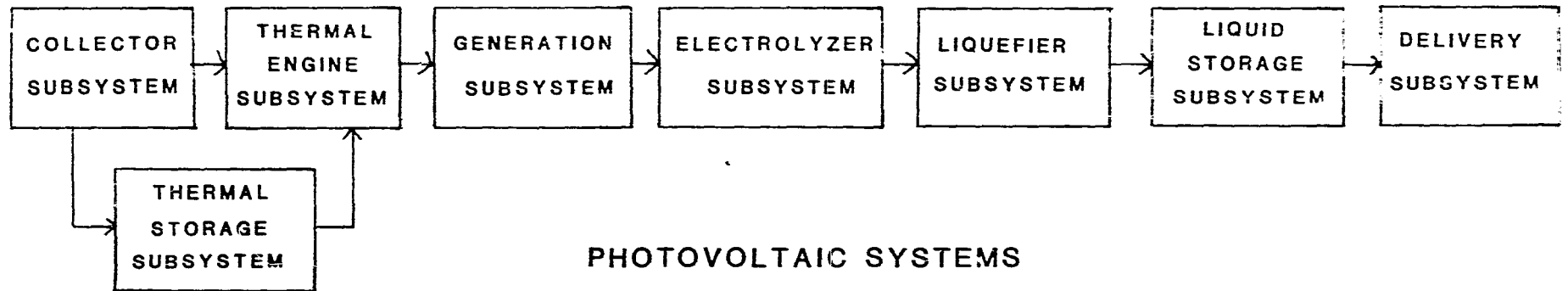
- 6% annual inflation rate
- 12% discount rate
- 48% income tax rate
- 2% property tax and insurance rate
- 10% investment tax credit
- 10-year depreciation period
- 20-year book life.

Capital costs and annual operating and maintenance expenses are specific to each system. Using levelized product costs, the basic objective is to rank the systems to allow the selection of one or two finalist candidates for final detailed analysis and conceptual design treatment.

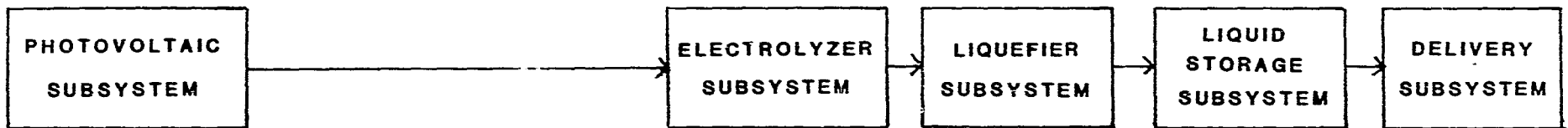
### General Screening Approach

The water electrolysis and conventional liquefier subsystems are common to all candidate systems. These subsystems are characterized by calculating their contribution to overall levelized liquid hydrogen product cost as a function of electrical power cost. Each system, from its non-fossil energy sources through its electrical power output, is then evaluated via the TAG model to obtain the levelized electricity cost. This is then used to determine hydrogen production and liquefaction costs. Two basic approaches for the electrolysis and liquefaction subsystems operation are considered: 24

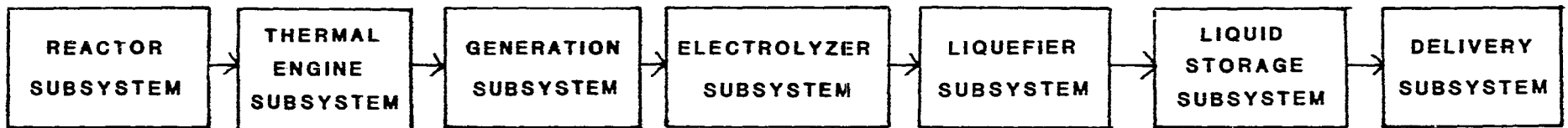
## SOLAR THERMAL ENGINE SYSTEMS



## PHOTOVOLTAIC SYSTEMS



## NUCLEAR SYSTEMS



## REMOTE SHIPPED PRODUCT SYSTEMS (e.g., OTEC)



Figure 7-1. SECOND SCREENING CONCEPTUAL CANDIDATE SYSTEMS

## CRITICAL EVALUATION OF POOR QUALITY

hour/day (around-the-clock) operation and operation only during periods of sunlight. First, the common-to-all systems water electrolyzer and hydrogen liquefier subsystems are treated. Then will follow the various non-fossil energy conversion subsystem evaluation.

### Electrolyzer

Water electrolysis facilities are highly modular, i.e., over a certain lower-sizing limit, as the plant capacity increases, costs increase about linearly, and there is little economy-of-scale effect inherent in the implementation of this technology. There is the possibility that with a sufficiently large order of similar equipment that unit costs could be reduced, which is considered later but not in this screening. Exemplary costs and space requirements were obtained from The Electrolyser Corporation in January 1983 (Reference 7-2). The units needed can be characterized by:

- 280 \$/kW (350 C\$/kW) (installed)
- 80% efficiency
- .15 m<sup>2</sup>/Nm<sup>3</sup>/hour.

The approach taken was to estimate costs for a plant able to produce 1 million pounds of hydrogen per year, then to derive costs per pound as a function of electrical power costs.

### 24-Hour/Day Plant Operation

Space required is 981 ft<sup>2</sup> which comes to \$29,430 assuming building costs of \$30/ft<sup>2</sup>. Electrical requirements are 2,555 kW. We use \$350/kW as an installed cost of the electrolyzers, the 20% increase from the uninstalled cost representing labor, ancillaries, piping, and electrical busbars. Thus, the capital requirements--including building--are \$923,700 for the one million pound-per-year plant. Annual operating and maintenance costs were taken as 2% of this number.

### Sunlight Hours Only Operation

The following estimate is based on using global tilted insolation which averaged 5.57 kWhr/day at the Florida Solar Energy Center (FSEC) from 1977 to 1982. This is an average of .232 kW/m<sup>2</sup>, or a factor of 4.3 below standard peak insolation of 1 kW/m<sup>2</sup>. Thus, to use electrical power as it is produced, the electrolyzer facility must be up-scaled by a factor of 4.3. Overall electrical consumption is the same as in the previous case. For such a plant, capital requirements are \$3,972,000 and O&M expenditures are \$79,000 per year (again, using 2% of the total plant cost figure).

These capital and O&M costs were then input into the TAG model with electrical power costs varied from \$.03 to \$.50/kWhr. Electrical use is 22.38 x 10<sup>6</sup> kWhr/year. The results for the two cases are shown in Figure 7-2.

### Liquefier

Basic data for conventional liquefaction plants were provided by C.R. Baker of the Linde Division of Union Carbide Corporation, as a consultant to the study team (see also Appendix C). Costs and other data for a range of plant sizes are shown in Table 7-1, and are normalized to pounds/year in Table 7-2. Economy of scale is evident for the larger plants both in costs and electrical requirements.

Table 7-1. BASIC LIQUEFIER DATA (Source: C.R. Baker, Linde Div., UCC)

Plant Size (Tons/Day)	$10^6$ lbs/yr	Requirements			Cost ( $10^6$ \$)
		Elec. (kW)	Cooling H <sub>2</sub> O (gpm)	15 psi Steam (lb/hr)	
8	5.84	4,030	2,300	280	12.5
15	10.95	7,260	4,200	525	19.5
20	14.60	9,490	5,500	700	24.0
25	18.25	11,800	6,800	875	28.3

Table 7-2. NORMALIZED LIQUEFIER DATA

Plant Size (Tons/Day)	Requirements				Cost (\$/lb/yr)
	Elec. (kW)	Cooling H <sub>2</sub> O (gal/lb)	15 psi Steam (lb/lbH <sub>2</sub> )		
8	6.05	207	.42		2.14
15	5.81	202	.42		1.78
20	5.69	198	.42		1.64
25	5.66	196	.42		1.55

For continuous operation, a plant sized at 8 T/day is assumed. Such a plant would cost \$2,140,000 and have an \$85,600 O&M budget (4%) exclusive of electricity costs. For operation only during daylight hours, the plant would be 4.3 times as large to handle periods of peak insolation, or approximately 35 T/day capacity. Using costs for a 25 T/day plant as representative, the capital cost for a  $10^6$  lb/year plant would be \$6,665,000 with an O&M budget of \$200,000 (3%). However, a start-up requirement, due to daily warmup will cost about 15% of capacity for the second mode of operation.

These values were input into the TAG model with the price of electricity varied as in the case of the electrolyzers. The results are shown in Figure 7-3. It is instructive to compare the graphs for electrolysis and liquefying costs (Figures 7-2 and 7-3). For either mode of operation, the electrolysis cost lines come close to going through the origin, indicating that the costs are dominated by the price of electricity and not capital intensiveness. The reverse is true for the liquefier cost lines which indicates that costs are strongly capital intensive, being secondarily affected by electrical power costs.

#### Gaseous Hydrogen Storage

The last item in common to all the systems to be screened is an assumed one day gaseous hydrogen storage facility between the electrolyzer plant and the liquefier facility to provide feedstock continuously. Capital costs were taken as \$.75/scf and O&M costs as 1% of capital. This yields \$386,300 in capital and \$3,900 per year in O&M for a plant sized at  $10^6$  lbs/year with no economy of scale foreseen. Levelized costs from the TAG model work out to \$.07/lb under the same financial conditions cited earlier.

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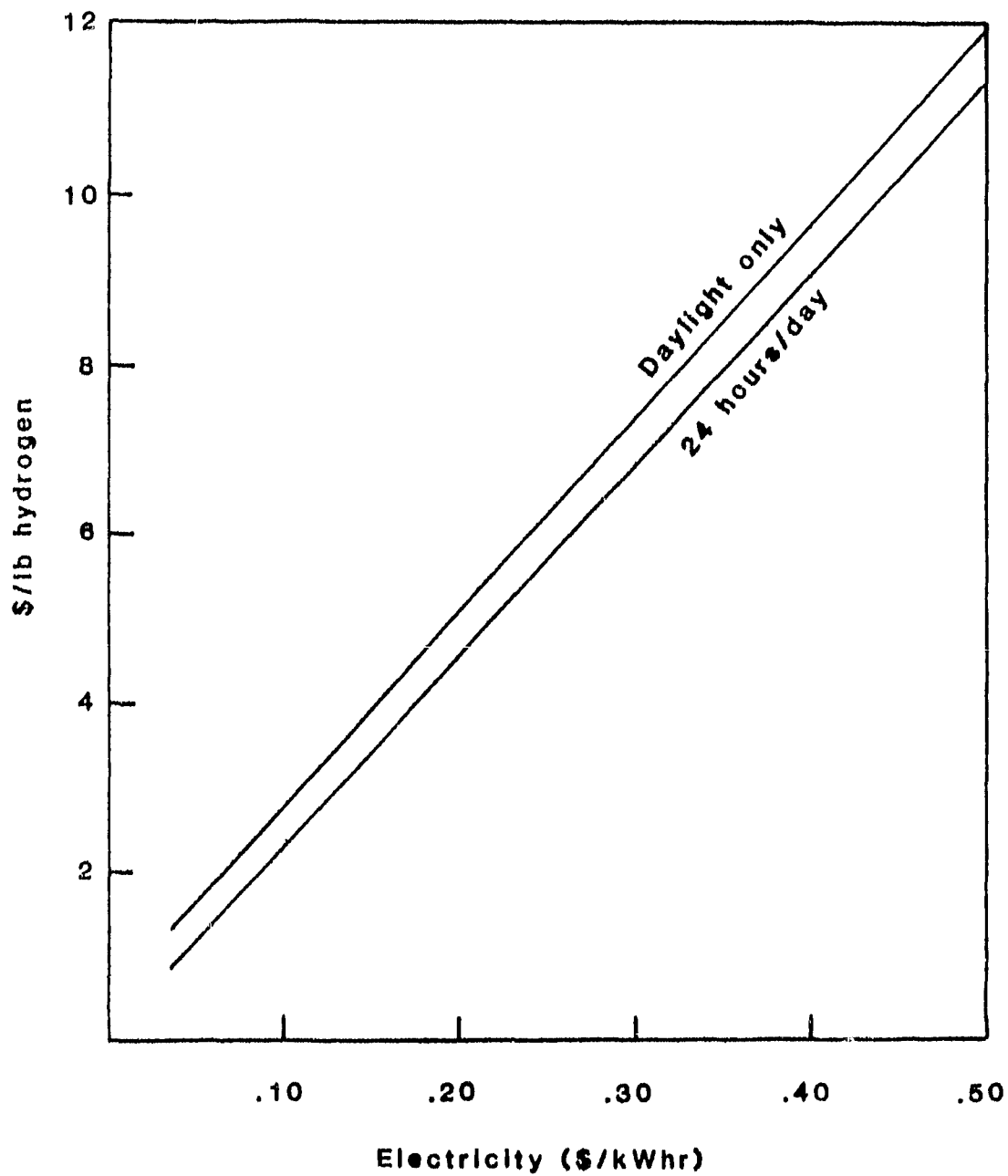


Figure 7-2. LEVELIZED COST OF GASEOUS HYDROGEN FOR TWO SCENARIOS VIA WATER ELECTROLYSIS VS. ELECTRICITY COST

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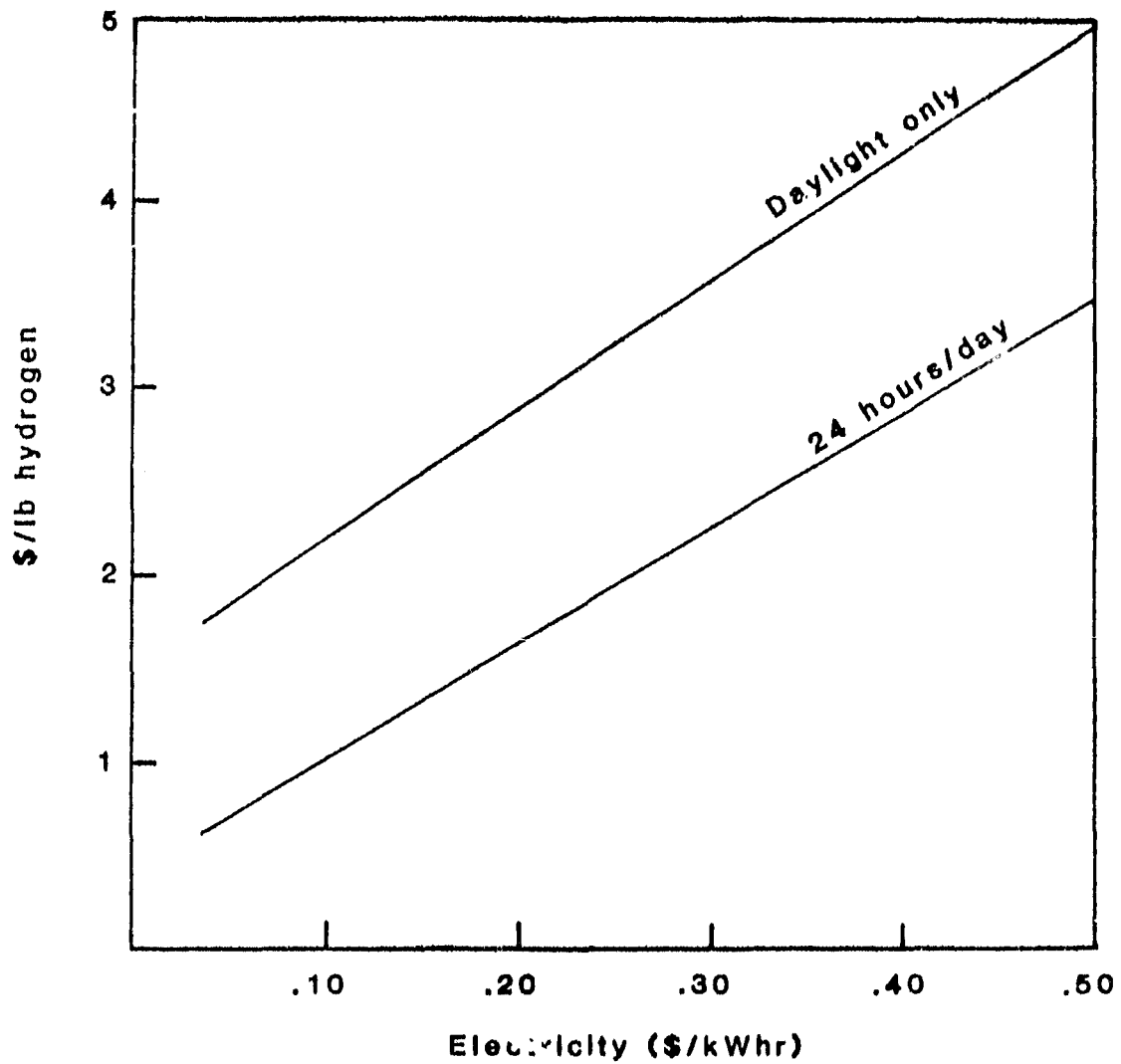


Figure 7-3. LEVELIZED COST OF LIQUEFYING HYDROGEN FOR TWO SCENARIOS  
VS. ELECTRICITY COST

## Cost of Photovoltaic Electricity

Each installed peak watt of PV array will yield 2.03 kWhr/year of electrical energy based on the FSEC data for tilted global insolation during the 1977-1982 period. Thus, an array designed to produce 1,000 kWhr/year would be sized at 493 peak watts at this location. PV installed costs over the wide range of from \$1 to \$12 per peak watt were used together with an annual O&M cost of \$50 (2% of \$10/Wp installation) to characterize a 1,000 kWhr/year array. By running these numbers through the TAG model, the levelized electrical power costs were obtained (Figure 7-4).

To the Study Team's knowledge, the lowest uninstalled PV module cost to date is on the order of \$5/Wp. Discussions with representative manufacturers (Reference 7-3) indicate that this number is expected to possibly drop below \$1/Wp within 5 to 7 years. Thus, for installed cost from \$1/Wp to \$8/Wp, electricity costs range from \$.15/kWhr to \$.68/kWhr (Figure 7-4).

## Distributed Flat Plate (Solar Thermal) Electricity Costs

As one version of a solar thermal system, the flat plate collector is a low-temperature system. Two variants are described with and without thermal storage (Figure 7-5). Since no particular economy of scale seems evident in such systems, costs are approximated for a system producing 1,000 kWe/year.

A system with thermal storage would be sized at .114 kWe (1,000 kWhr/8,760 hours). The engine/generator subsystem is assumed 8% efficient (Reference 7-4), so 12,500 kWhr input of thermal energy is required over the year. Typical flat plate collectors have a 60% efficiency (Reference 7-5) requiring 20,830 kWhr of insolation per year for this system. Each square meter of collector receives 2,030 kWhr/year of tilted global sunlight, so 10.26 m<sup>2</sup> of collector (3.45 32-ft<sup>2</sup> panels) is needed. Costs for the organic rankine engine/generator are assumed as \$1,000/kW (Reference 7-4) and \$500/panel (installed) for the collectors.

Thermal storage costs are taken to be \$8/kWhr (Reference 7-6). The system requires about 18 hours storage and both a high- and a low-temperature thermal storage reservoir costs of \$411. Without thermal storage, the engine/generator must be sized to handle the peak power from the collector panels:  $10.26 \text{ m}^2 \times 1 \text{ kW/m}^2 \times 0.6 \times 0.08 = .492 \text{ kW}$ . A summary of these costs is shown in Table 7-3.

Table 7-3. SUMMARY OF COSTS FOR THERMAL STORAGE

	<u>With</u>	<u>- Thermal Storage</u>	<u>- Without</u>
Engine/Generator	\$114		\$492
Storage	411		--
Panels	1,725		1,725
TOTAL COST	2,250		2,217
O&M @ 2%	45		45
Electrical Cost (from TAG Model)	\$ .412/kWhr		\$ .406/kWhr

LEVELIZED ELECTRICITY COST  
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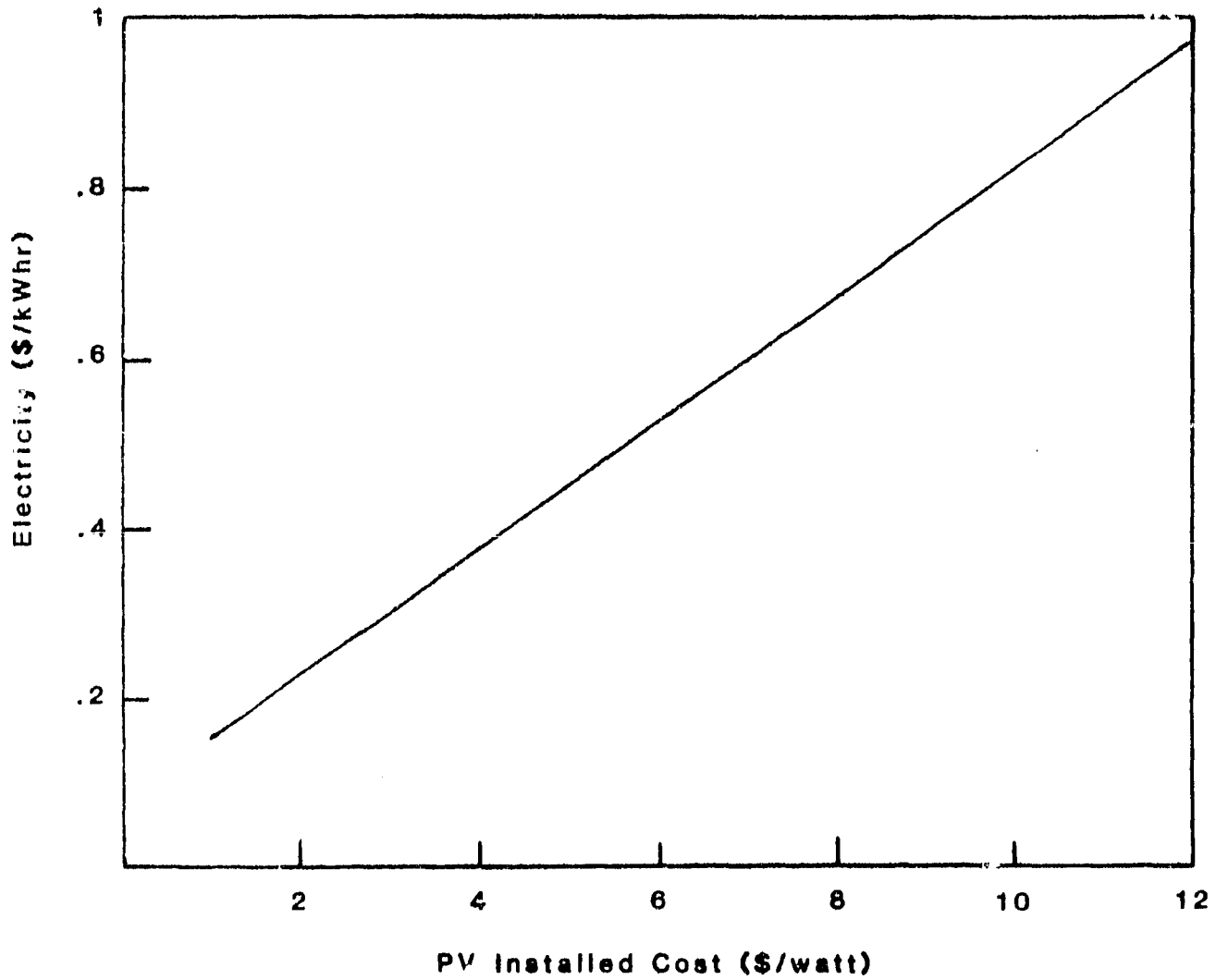


Figure 7-4. LEVELIZED ELECTRICITY COST VS. PHOTOVOLTAIC INSTALLED COST



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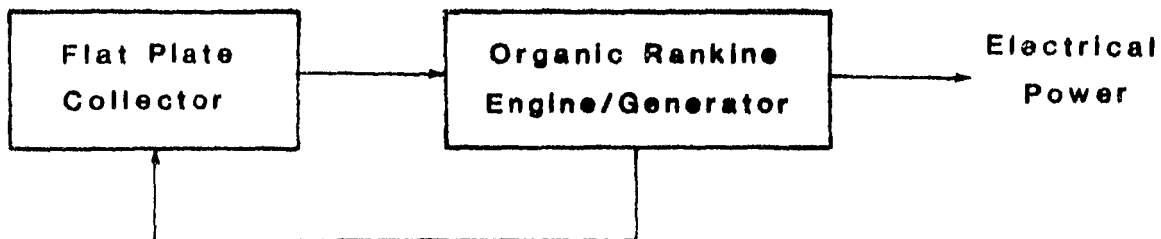
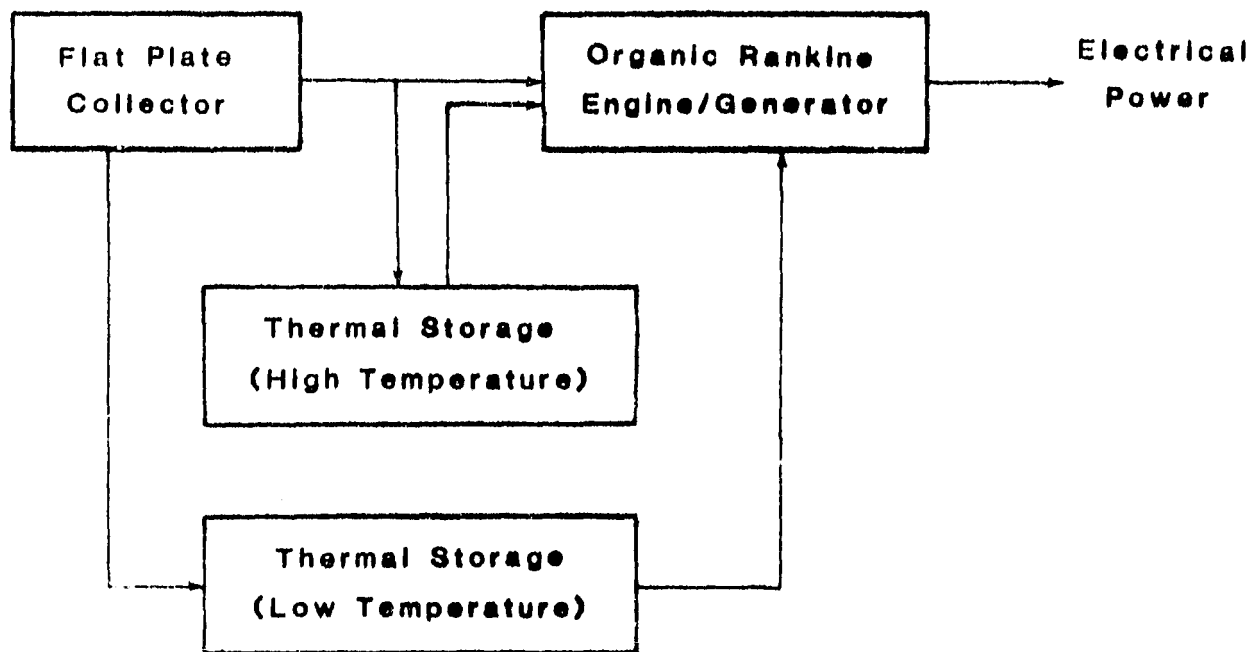


Figure 7-5. CONCEPTUAL DESIGNS OF FLAT PLATE COLLECTOR SOLAR THERMAL SYSTEM

## Power Tower (Solar Thermal) Electricity Costs

As a basic reference, the conceptual study for the "Solar 100" power tower system (References 7-7 and 7-8) located in the U.S. Southwest provides the following parameters:

- $489 \times 10^6$  kWhr/year electrical output
- $\$431 \times 10^6$  construction cost
- $2,5576 \text{ kWhr/m}^2$  direct normal insolation.

Using these numbers with a 2% O&M annual expense yields an electrical cost of \$.16/kWhr when taken with the remaining self-consistent assumptions.

The same facility "transplanted" to KSC would yield  $324 \times 10^6$  kWhr/year due to the lower direct normal insolation of  $1,705 \text{ kWhr/m}^2/\text{year}$ --the 1977-1982 FSEC average value. This assumes that parasitic losses, etc., scale only with insolation levels. To produce 6 million pounds per year of liquid hydrogen requires  $171 \times 10^6$  kWhr/year of electricity. Since the Solar 100 design is a two-tower, two-field design, it appears that by simply using half the design the KSC needs can be roughly met.

Thus, we use a capital cost of  $\$215 \times 10^6$  to produce  $162 \times 10^6$  kWhr/year and take O&M to be 2%. The TAG model then suggests an electricity cost of \$.243/kWhr for this design in the KSC environment, some 50% over the Southwest location situation.

## Distributed Concentrating Systems

A discussion with Spencer Carlisle of Southern California Edison, who has been evaluating these systems for the utility, indicated that costs and land area required are approximately the same as for large point focus collectors such as Solar One. Accordingly, the study team felt that concentrating systems could be typified for screening purposes by the power tower alone. Therefore, concepts such as parabolic "troughs," steerable "dishes," etc., were not specifically examined.

## Modular HTGR Electrical Costs

No cost estimates other than the statement that costs would be generally competitive with other nuclear generating plants was obtained for the modular HTGR case as the leading nuclear possibility. Due to the small-size plant of only 2 to 3 modules anticipated, the study team felt that electrical costs would be higher than for larger plants. Accordingly, parametric electrical costs of \$.08, \$.12, and \$.16 per kWhr were used to characterize such a small nuclear plant at KSC.

## OTEC Electrical Costs

A recent review article on OTEC systems (Reference 7-9) suggests \$3,500/kW as an approximate capital cost. Using this value and a 3% O&M figure, electrical power costs are estimated at \$.08/kWhr. However, since no OTEC plant has actually been constructed, the study team felt it prudent to use values of \$.08, \$.12, and \$.16 per kWhr to characterize this system candidate for screening purposes.

An OTEC platform producing liquid hydrogen as its energy product would obviously have the water electrolysis and liquefaction facilities onboard. This requires an additional liquid hydrogen storage facility to accumulate product sufficient to fill an envisioned liquid hydrogen tanker ship. A 1976 IGT study estimated shipping costs at \$2/10<sup>6</sup> Btu. When inflated to 1983 dollars, this translates to a \$.21/lb incremental cost. The estimate was based on a 15,000 bbl ship (3735,000 lbs hydrogen). A storage dewar sufficient to accumulate this quantity of product would cost \$3.18 x 10<sup>6</sup> (Reference 7-10). With 1% O&M, the TAG model yields a levelized storage cost increment of \$.09/lb.

#### Liquid Hydrogen Product Costs

With the levelized electricity costs for each system in hand, the previously discussed costs of producing and liquefying the hydrogen (e.g., see Figures 7-2, 7-3), were integrated to obtain final product liquid hydrogen costs at the KSC site. The results are presented in Table 7-4.

Table 7-4.

System	Non-Fossil Elec. Cost (\$/kWhr)	GH <sub>2</sub> Prop. Cost	GH <sub>2</sub> Storage \$/lb	Liq. Cost	Shipping/ Storage	Total
Power Tower	.24	5.50	.07	1.93	--	7.50
Distributed Flat Plate						
- With Thermal Storage	.41	9.30	.07	2.95	--	12.32
- W/O Thermal Storage	.41	9.90	.07	4.30	--	14.27
Photovoltaic						
- \$8/Watt	.68	15.90	.07	6.10	--	22.07
- \$6/Watt	.53	12.60	.07	5.10	--	17.77
- \$4/Watt	.38	9.20	.07	4.10	--	13.37
- \$2/Watt	.23	5.85	.07	3.10	--	9.02
- \$1/Watt	.15	4.20	.07	2.55	--	6.82
OTEC						
- \$.08/kWhr	.08	2.00	.07	.95	.30	3.32
- \$.12/kWhr	.12	2.85	.07	1.20	.30	4.42
- \$.16/kWhr	.16	3.70	.07	1.45	.30	5.52
Modular HTGR						
- \$.08/kWhr	.08	2.00	.07	.95	--	3.02
- \$.12/kWhr	.12	2.85	.07	1.20	--	4.12
- \$.16/kWhr	.16	3.70	.07	1.45	--	5.22
Conventional (Ref.)	--	--	--	--	--	5.63

In order to provide some basis for evaluating these cost, the present cost of \$2.72/lb as delivered to KSC was subjected to 6% inflation and a 3% escalation over inflation to characterize increases in natural gas and electricity costs. The levelized cost for a 20-year period is \$5.63/lb as noted.

The power tower uses its thermal molten salt storage to provide electricity 24-hours/day, as does the distributed flat plate system with its thermal storage. OTEC and the modular HTGR are assumed to operate 24-hours/day. The distributed flat plate system without thermal storage and the PV system are assumed to operate only during daylight hours and hence use the upper curves in Figures 7-2 and 7-3.

References Cited in Section 7

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- 7-2. Personal communication with Gerald Crawford, The Electrolyser Corporation, Toronto, Canada, January 1983.
- 7-3. Personal communication with Ted Swanson and Jeff Shingleton, Mueller Associates, Inc., Baltimore, MD.
- 7-4. Personal communication with SPS, Inc., Miami, FL.
- 7-5. "Solar Products Specification Guide," prepared for Solar Age Magazine, February 1983 Edition.
- 7-6. Personal communication with R.R. Tison, E:F Technology, Inc., St. Johns, MI.
- 7-7. Roland, J.R. and Ross, K.M., "Solar Central Receiver Technology Development and Economics--100 MW Utility Plant Conceptual Engineering Study," McDonnell Douglas Astronautics Company and Southern California Edison Company, respectively, paper presented at the 10th Energy Technology Conference, Washington, DC, 28 February-2 March 1983.
- 7-8. Ross, K.M., Roland, J.R., and Bouma, J., "Solar 100--Conceptual Study (Executive Summary)," final report, 3 August 1982.
- 7-9. Review article published in Cornell Engineering Quarterly, Vol. 17, No. 1, Summer 1982.
- 7-10. Baker, C.R., Linde Division, Union Carbide Corporation, memorandum to E:F Technology, Inc., 4 February 1983 (see Appendix C ).

## 8. FINALIST CANDIDATE SYSTEMS CONCEPTUAL DESIGN AND COST ANALYSIS

### Introduction and Overview

The second economic screening of the system candidates shows that to meet a 1987, 1992, or a somewhat later IOC deadline, only a handful of candidate systems can be practically considered. While OTEC and the modular HTGR systems offer significant promise of providing a competitively-priced product, until more experience with these systems is gained including actual full-scale implementations, little more can be added through a study of the present scope to alter the stance of the advocates: "electricity from these systems will be competitively priced."

The lack of certain physical and energy resources at the KSC facility also helps reduce the number of systems admitted to the "finalist" category. The two finalist systems chosen for further, in-depth investigation are those which depend on the solar resource (insolation). In the case of direct (specular or beam) insolation, the distributed central receiver point focus system (Power Tower) has been identified as the most promising candidate. Capitalizing on the relatively high quantity of global or indirect insolation at KSC, the photovoltaic system has been identified as a prime choice.

Sufficient land at KSC has been identified, as will be seen, to permit the construction of such systems. When potential coproducts are considered, only the liquid oxygen coproduct is practicable considering the characteristics of both water electrolysis and conventional liquefaction technologies. Solar electricity itself is too expensive to compete with the local utility (see Section 6 for approximate costs), and the low-grade reject heat from the electrolyzers, though interesting in potential, is not of sufficient value to mount a major effort for its reclamation, e.g., for driving absorption chillers.

Provided the trend toward less expensive Photovoltaics (PV) installed costs can continue (see Figure 8-1), both the PV and Power Tower (PT) systems can begin to compete with conventional liquid hydrogen product costs when the latter is escalated by 3% per year over inflation. While a detailed design of a PT system exists for desert insolation producing grid a.c., no large-scale design for a PV system devoted to producing hydrogen exists to the study team's knowledge. The logic of approach used in detailing the two selected systems analyses was, accordingly:

- PV---estimate a representative "module" sub-array size to integrate into a full-scale PV array system; determine the cost/throughput implications of several methods of interconnecting these modules (i.e., a.c. grid, d.c. bus, distributed electrolyzers with gas-main grid)
- PT---estimate the output of Solar 100 type of hardware in the KSC reduced-intensity solar environment.

Final estimated product liquid hydrogen costs are then derivable and can be compared to projections of those for today's conventionally-produced liquid hydrogen on a common basis.

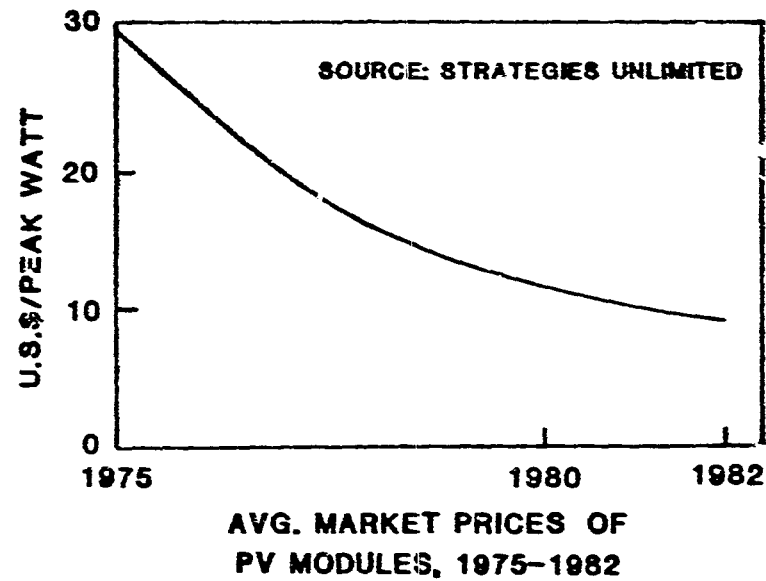
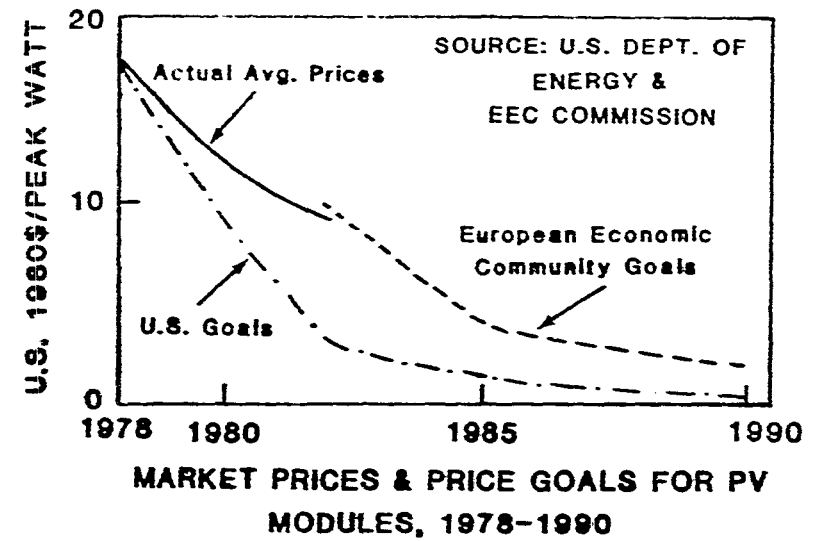
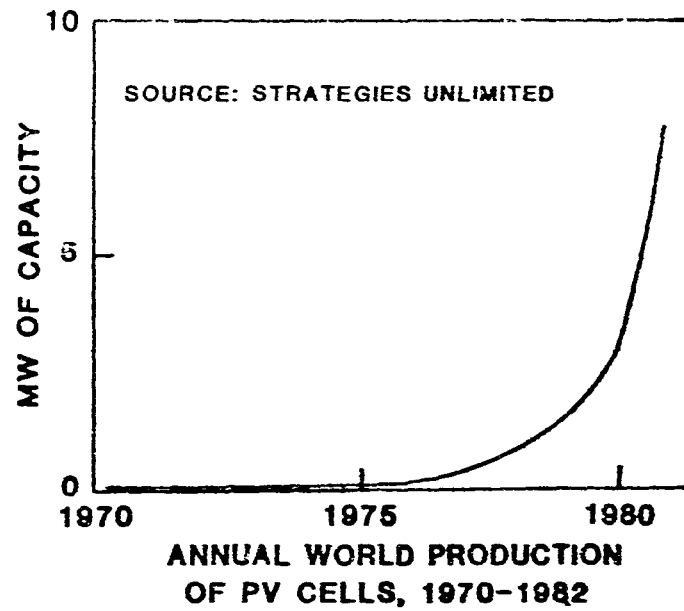


Figure 8-1. PV COST AND PRODUCTION PROJECTIONS

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PV System

Related to the Study Team's in-process conceptual design activities for the PV "finalist" system, a technical paper was prepared and presented at the 20th Space Congress meeting in Cocoa Beach, Florida, 26-28 April 1983. This paper, reproduced in Appendix D, evaluated three configurations of interconnected 400-kWp PV "modules" or sub-arrays to achieve approximately 6 million pounds of product liquid hydrogen from a 100-MWp PV array. In all three cases, two arrays are defined. The first (67.6-MWp) provides power to the electrolyzers which operate only during periods of sunshine. The second (32-MWp), via a.c. inverters and battery storage, is used to power a liquefier plant 24 hours/day. The round-the-clock liquefier powering requirement is a consequence of the basic upsizing capital costs plus operational difficulties (and further costs) if the liquefier facility must be cycled off and on. Two versions of a central electrolyzer facility were considered (plus, as will be seen, a "distributed electrolyzer" version):

- Modules produce a.c. power via inverters, distribute this conventionally to the electrolyzer plant, where it is rectified back to d.c. power
- Modules connected by a d.c. copper bus array directly to the electrolyzer facility, eliminating the inverter/rectifier losses and capital costs.

Especially since the electrolyzer reject-heat turns out to have minimal value, a third alternative electrolyzer and gas mains used to deliver the hydrogen and oxygen gas to the liquefier was evaluated. This is referred to as the "distributed electrolyzer" approach. Whereas collection of low-temperature electrolyzer waste heat is deemed practical in the "central electrolyzer" approach, it is not considered practical in this case.

It was shown that of the three options considered, the "distributed electrolyzer-gas mains" option involved the lowest specific capital cost (\$/lb hydrogen/year), closely followed by the d.c. busbar centralized electrolyzer option. The "obvious" choice--the use of inverters and rectifiers and an a.c. grid--was the most expensive.

The Space Congress paper provided a solid "early on" starting basis for a more refined conceptual design of a PV stand-alone system for KSC liquid hydrogen production. The reader is urged to examine the paper for the basic design approaches, detailed trade-offs, etc., since this information is not repeated in the present text. However, subsequent investigation revealed several small opportunities for improvement in the overall system design. In addition, it was determined that the land area could be reduced by assuming somewhat higher PV-module efficiencies, and switching to the use of a fixed array, rather than the periodic-variable tilt system. Using the general framework of experience of this earlier design, small changes were introduced by working "backwards" from a liquid hydrogen output of 5.9 million lbs/year (10 million gallons) with corresponding liquid oxygen coproduct.

#### Hydrogen and Oxygen Liquefaction

In this study, Linde provided a nominal conceptual design of a suitable hydrogen and oxygen liquefaction system based on current conventional technology. Details are discussed directly in correspondence from Mr. C.R.

Baker of Linde (Appendix C). With stoichiometric quantities of oxygen being available from the electrolysis process, this oxygen can be liquefied in the basic hydrogen liquefaction facility. This can be accomplished by substantially up-sizing the built-in nitrogen liquefier subsystem so that sufficient liquid nitrogen is produced to directly liquefy the oxygen by heat-exchange.

The resulting hydrogen and oxygen liquefaction system is configured as schematically shown in Figure 8-2, with key input/product characteristics quantified. Note is made that the input hydrogen amounts are some 2.5% higher than the output amount. This difference is explained below, in perspective with conventional industrial practice.

Figure 8-3 shows a rough plan layout of the product liquefaction facility as it would serve both the liquid hydrogen and oxygen product requirements. Included are liquid storage dewars capable of storing approximately 3 weeks' production amounts. This timing roughly matches projected STS operations as estimated for ca. early 1990's.

The basic liquefier costs for a range of sizes from 8 to 25 tons/day LH<sub>2</sub> are presented below as provided by Linde.

#### BASIC HYDROGEN LIQUEFIER COSTS AND INPUT REQUIREMENTS

	Plant Size (Tons/H <sub>2</sub> per day)			
	8	15	20	25
Plant Cost (10 <sup>6</sup> \$)	12.5	19.5	24.0	28.3
Electricity (kW)	4,030	7,260	9,490	11,800
Cooling H <sub>2</sub> O (gal/min)	2,300	4,200	5,500	6,800
15 psi steam (lb/hr)	280	525	700	875
Annual O&M (10 <sup>3</sup> \$)	730	840	910	970

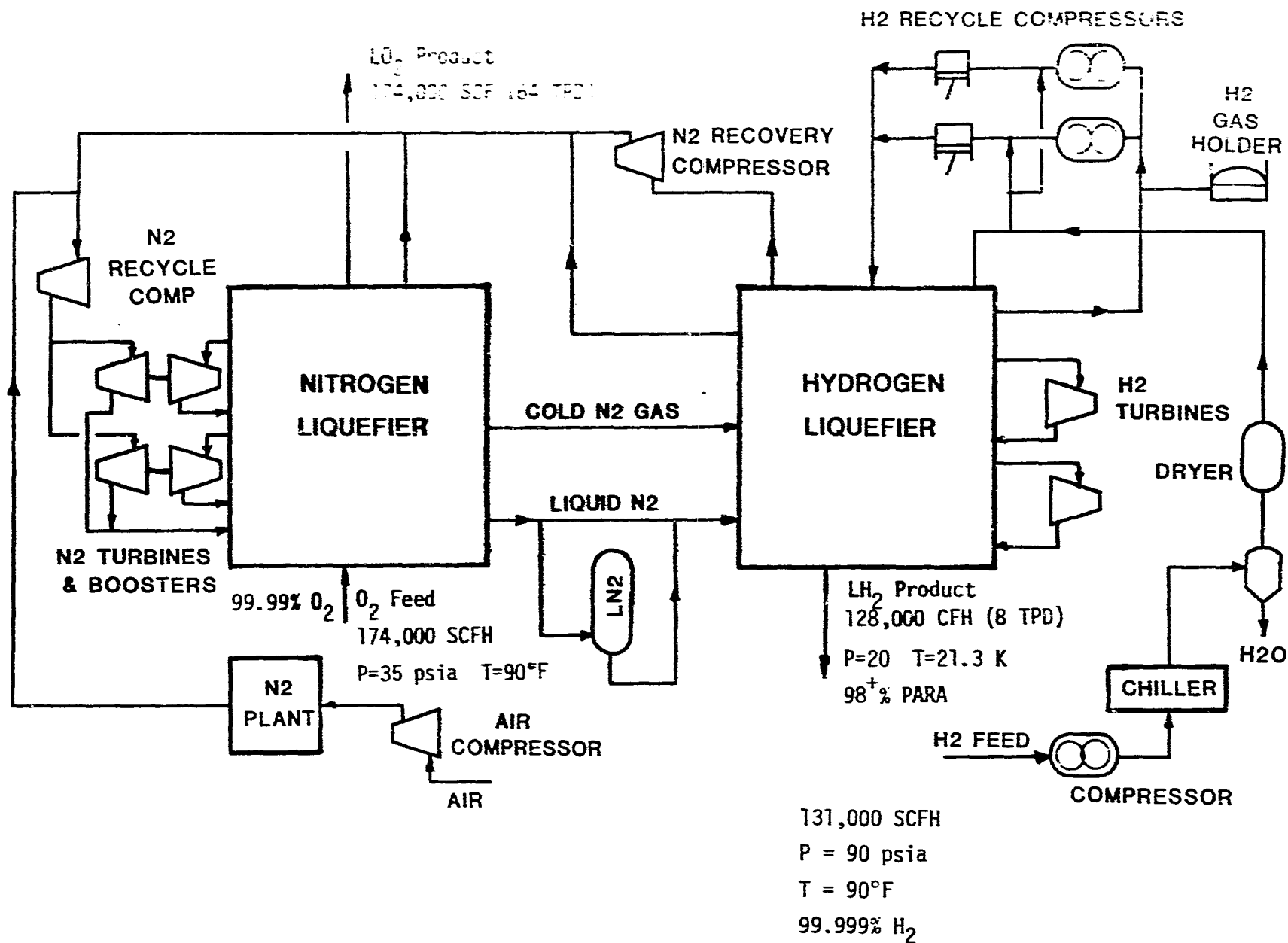
#### ADDITIONAL TO LIQUEFY THE OXYGEN AS WELL:

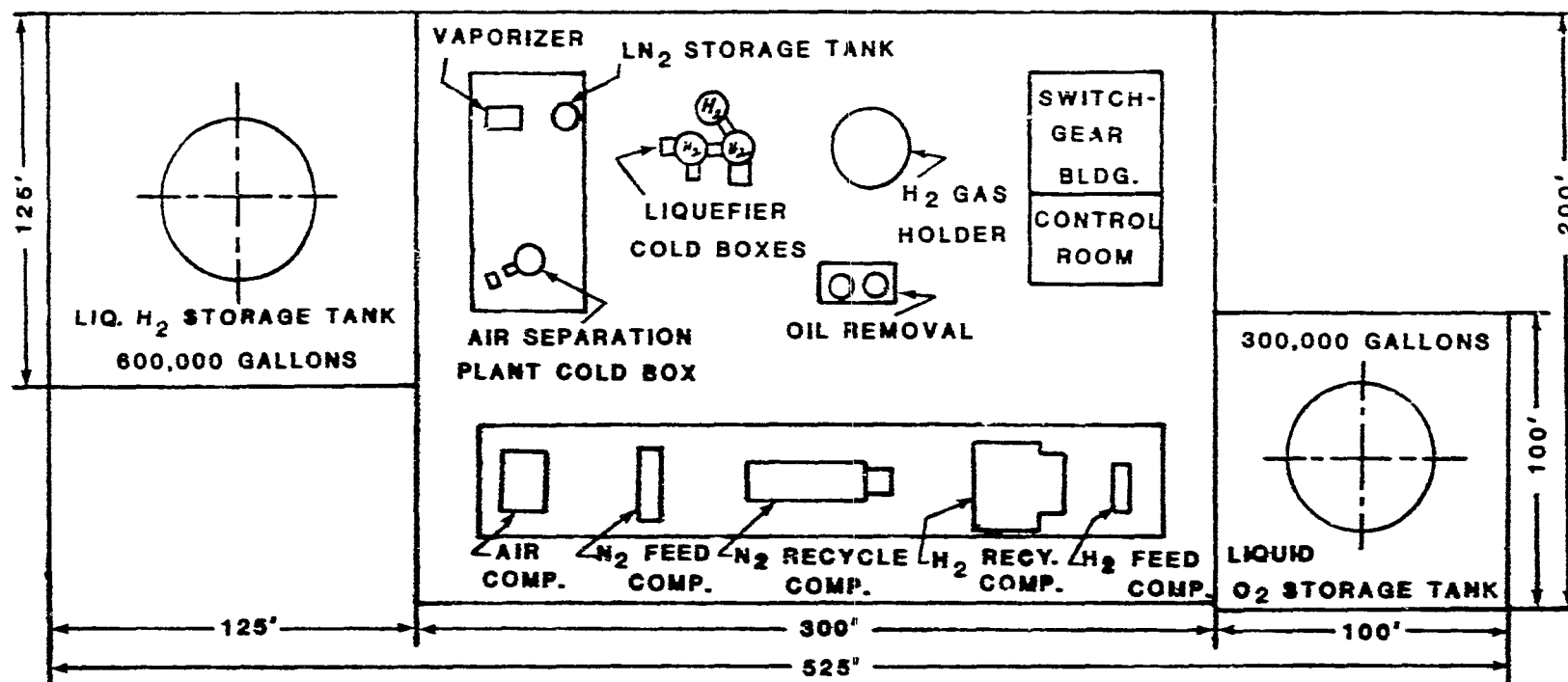
O <sub>2</sub> Rate (T/day)	63.5	119.0	158.7	198.4
Plant Cost (10 <sup>6</sup> \$)	2.1	3.0	3.6	4.1
Electricity (kW)	1,450	2,600	3,400	4,200
Annual O&M (10 <sup>3</sup> \$)	21	30	36	41

Costs are for battery limits, complete liquefier installed. Existence of cooling H<sub>2</sub>O, 15 psig saturated steam, electrical substation, and storage tanks for liquid assumed at or just outside of battery limits.

Conventionally, there is a significant physical loss of hydrogen in the liquefaction process due to leakage. Linde estimates that this loss, originating mainly at the compressor and turbine shaft seals and in the cold box can be held to 2.5% for only moderate added cost. This is in contrast to an 8.3% loss with many systems installed today. Because of the relatively expensive hydrogen, these improvements are cost effective for solar-based production facilities. The \$80,000 added cost for an 8 ton/day plant is, hence, quite tolerable (Reference 8-1).



ORIGINAL QUALITY  
OF POOR QUALITYFigure 8-2. HYDROGEN AND OXYGEN LIQUEFIER FACILITY (8 T/day LH<sub>2</sub> and 64 T/day LO<sub>2</sub>)



- 8 TPD LH<sub>2</sub>, 64 TPD LO<sub>2</sub>
- CONTINUOUS OPERATION (WITH UPSTREAM STORAGE)
- LIQUEFIED CAPITAL COSTS AT  $\$1.85 \times 10^6$ /TPD
- 3 WEEKS LIQUID STORAGE

Figure 8-3. COMBINED HYDROGEN AND OXYGEN LIQUEFIER  
(Source: Linde Division)

## Water Electrolysis

Thus, to achieve 5.9 million pounds of liquid hydrogen (10 million gallon nominal target), we must electrolyze water to produce 6.05 million pounds of gaseous hydrogen per year. Based on liquid product and operating 365 days/year, a liquefier must be sized at 8.08 tons/day at a capital cost of  $\$14.83 \times 10^6$ . The electrical requirements are 5.53 MW around the clock. We assume 8 hours operation from the PV array and 16 hours operation from battery storage (0.7 storage efficiency,  $\$100/\text{kWhr}$ ), requiring 171.0 MWhr/day. Assuming the inverters are 95% efficient, an average PV daily requirement of 180 MWhr/day is required to liquefy the product gases (both hydrogen and oxygen) from the electrolyzer.

Liquid storage to cover 22 days operations at KSC, as discussed next, costs  $2.4 \times 10^6$  \$ for the hydrogen and  $1.2 \times 10^6$  \$ for the oxygen (Reference 8-2). One day's gas storage for both gases using LPG container technology is estimated at  $4.6 \times 10^6$  \$. Electrolysis requires 22.38 kWhr/lb  $\text{H}_2$  at 80% efficiency, requiring 370.6 MWhr/day for the 8.28 T/day needed as input to the liquefier. Specific illustrations of the electrolyzer hardware approaches selected are provided in the systems-level descriptions of the PV- and PT-based finalist systems.

Electrolyzer costs are based on the assumption of large-scale production economics and are taken to apply equally to all manufacturers and types (viz., alkaline unipolar, alkaline bipolar, SPE). Costs are assumed to be  $\$2000/\text{kW}$  installed, without and with power conditioning.

### The 400-kWp Modular PV Sub-Array

Changing the tilt angle of such a large PV array 10 times per year as assumed in the previously mentioned Space Congress paper was judged by Mueller Associates' engineers to introduce needless complications raising the mounting structures costs and increasing O&M manpower costs. Also, it was felt that the assumption of 8% efficient panels was excessively conservative. Accordingly, the panels are now projected to be placed at a fixed angle based on the latitude. This allows the spacing between rows to be reduced to 7.62 m, thus saving land area. Using 12% as an achievable efficiency reduces the sub-array size to 88.9 m by 91.4 m with 12 rows of panels running East and West (Reference 8-3). Figure 8-4 shows the basic geometry of the 400-kWp modular subarray.

Based on comparisons between the experimental FSEC solar PV residence (fixed array) and the tilted global insolation measured with varying tilt angles throughout the year, the fixed array is estimated to receive 10% less insolation throughout the year than the configuration used in the Space Congress paper. Each 400-kWp module will produce 2.01 MWhr/day based on a 10% reduction of the 1977-1982 FSEC measured tilted insolation. If the array is directly interfaced (i.e., without maximum power tracking) to the electrolyzer, there is estimated to be a 4% average mismatch and low insolation loss, resulting in 1.93 MWhr/day energy actually applied to the electrolyzers.

### Overall System PV Array

Figure 8-5 schematically shows the system design and integration layout of the total system using the previously-discussed (e.g., see Appendix D)

186 POWER ELECTROLYZERS  
89 POWER LIQUEFIER (AND BATTERY STORAGE)  
275 TOTAL

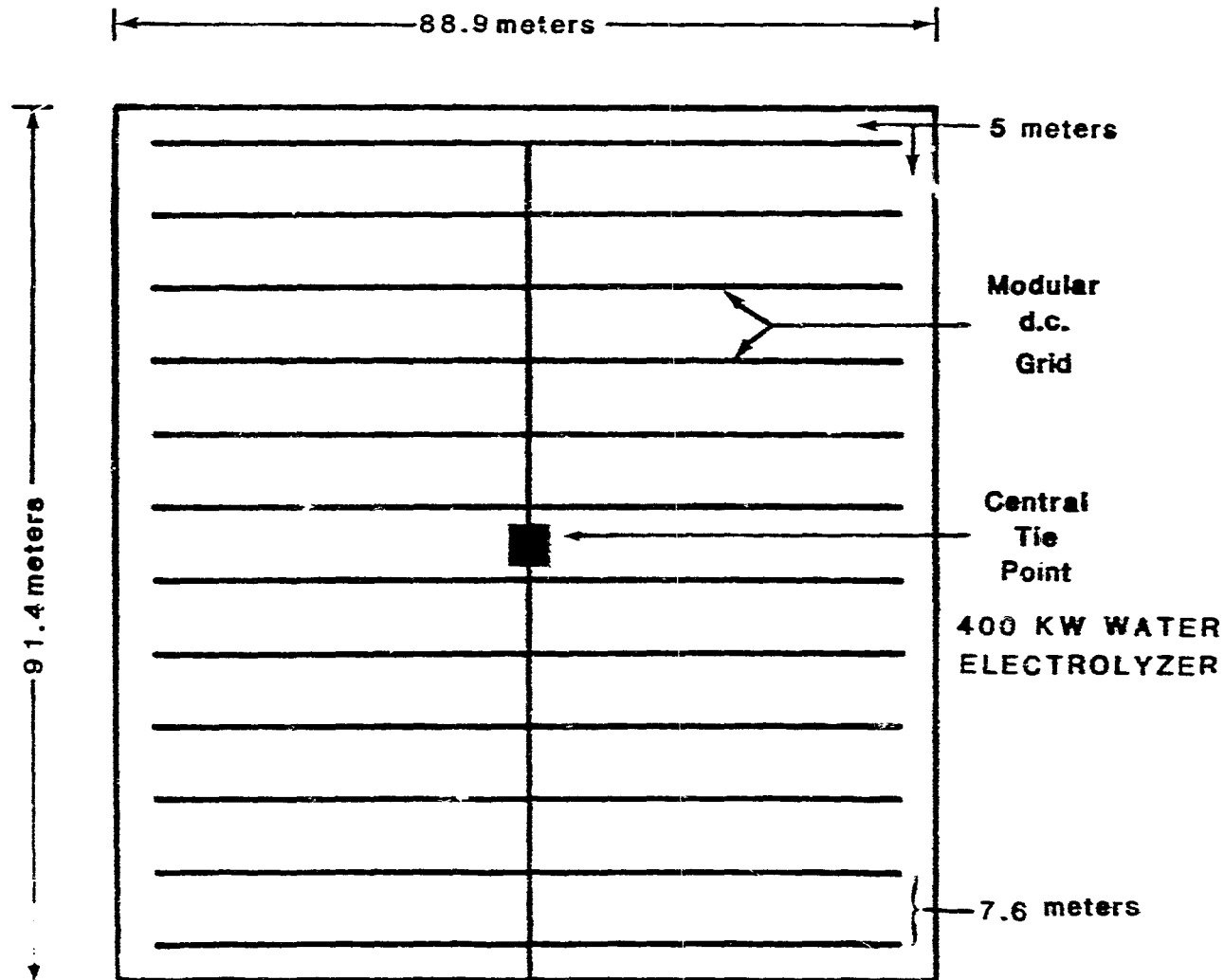


Figure 8-4. PV SUB-ARRAY: DISTRIBUTED ELECTROLYZER

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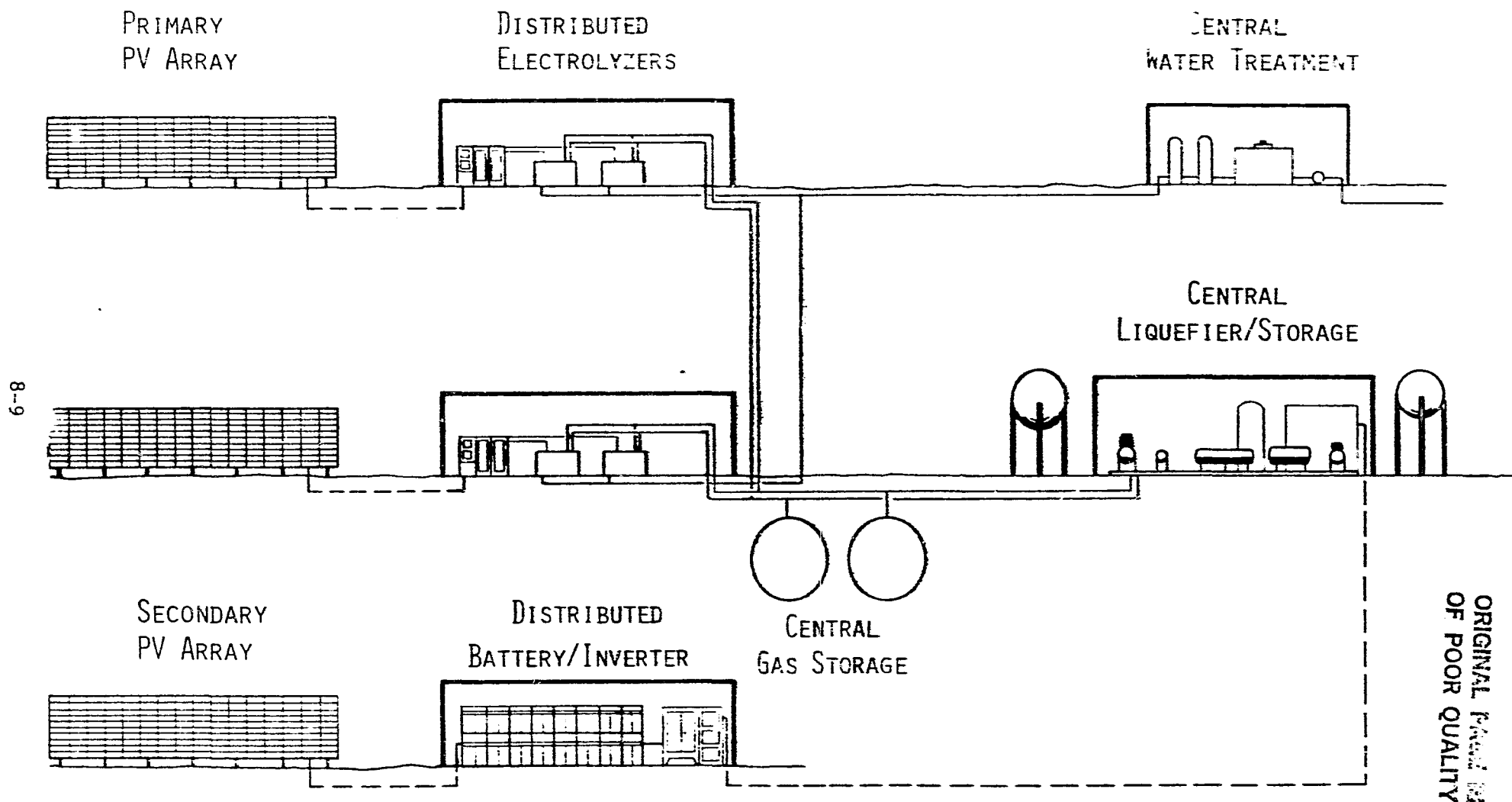


Figure 8-5. PHOTOVOLTAIC SYSTEM

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"distributed electrolyzer" approach. A representative electrolyzer unit for this multi-unit application is suggested in Figure 8-6. Although the Teledyne 50-kWe design shown is about one-tenth that required, the physical layout and dimensions would not be expected to change much in the needed upsizing. Basically, the "cell stack" central to the unit would use an increased-area cell and, perhaps, additional cells in the stack. Since directly-connected DC power is available from the adjacent PV array, the large rectangular power conditioning unit (rear of sketch) could be eliminated, or at least substantially reduced in size. The perspective-view sketch of Figure 8-7 reflects the essentials of the design in which the various arrays will be repeated in a close-packed, regular-geometry fashion as noted below.

The array to drive the electrolyzers is composed of 192 400-kWp DC-producing sub-array modules, while the array for the liquefier is composed of 90 such modules. The latter provides AC power through storage-battery inverter equipment. Peak power for the two arrays is 76.8 MW and 36 MW, respectively. The overall sizing of the facility is indicated in Figure 8-8 and a nominal KSC-siting situation is shown in Figure 8-9.

Summary of Capital and O&M Costs for PV Systems

	<u>Capital*</u>	<u>O&amp;M</u>
PV for electrolyzer	38.4 - 153.6	---
PV for liquefier	18.0 - 72.0	---
TOTAL PV	56.4 - 225.6	1.1
Liquefier	14.8	.76
Gas Storage	9.2	.092
Liquid Storage	3.6	.036
Interconnections & Electrolyzer	15.4	.308
Inverters, Grids & Batteries	9.3	.56
TOTALS	108.7 - 277.9	2.856

\* Note: PV capital costs are as installed for two values--\$.50 and \$2.00/Wp, respectively.

The estimation of liquid hydrogen product costs (based on these costs) is provided subsequently, following the characterization of the Power Tower system.

Power Tower System

A set of excellent design and analysis reports covering the proposed "Solar 100" Power Tower 100 MWe (net) generating facility concept has been prepared by Southern California Edison, Bechtel, and McDonnell Douglas for a southwest U.S. desert location. Liaison with these organizations was carried out in the course of the study. This design provides for 100-MWe net design output for 16 hours per day, producing conventional grid a.c. power (References 8-4 and 8-5).

As derived in the PV system analysis above, the basic requirement for 10 million gallons of liquid hydrogen is equivalent to 180.0 MWhr/day for the liquefier subsystem and 370.6 MWhr/day d.c. to operate the water electrolyzer

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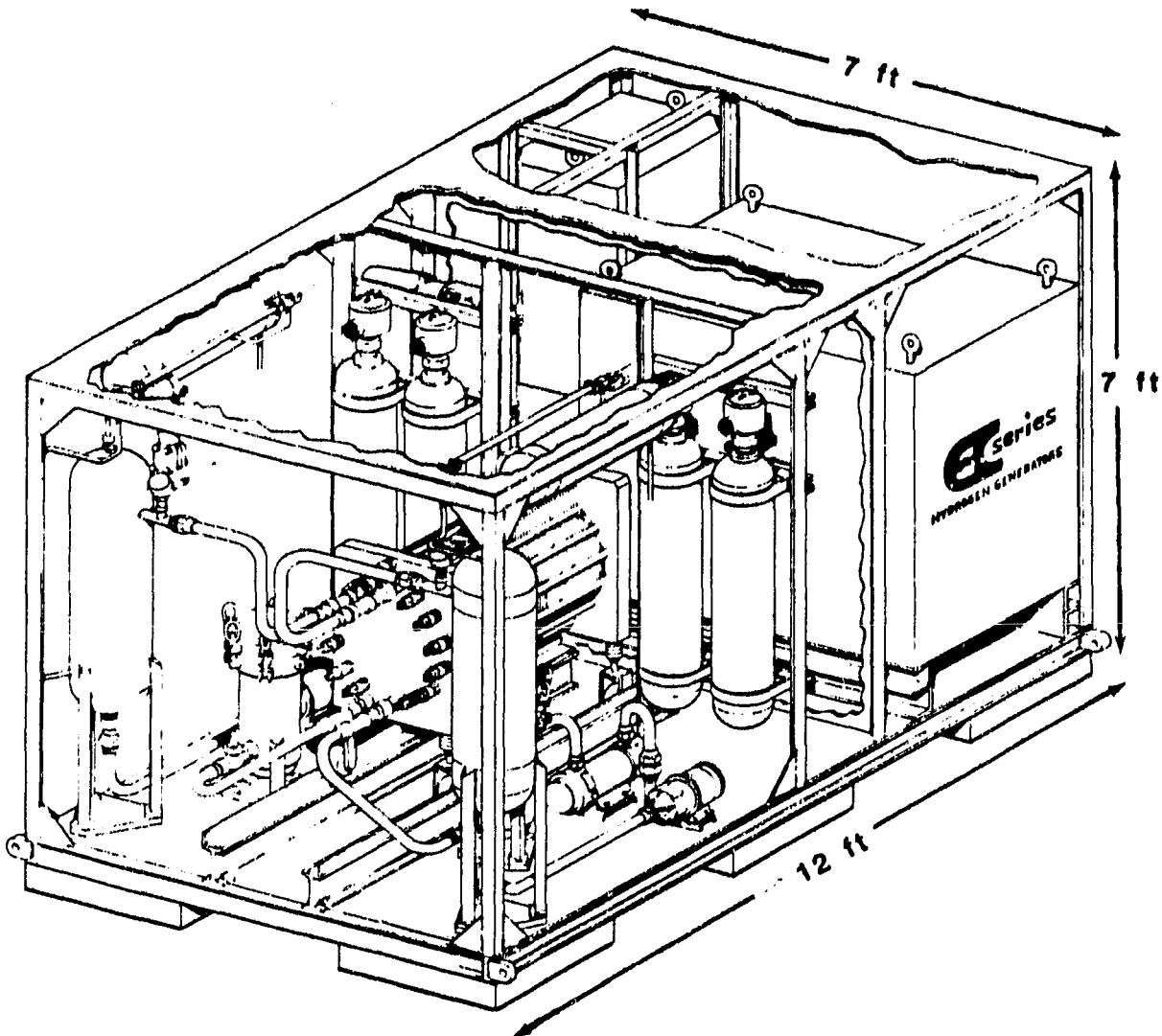


Figure 8-6. TYPICAL WATER ELECTROLYZER

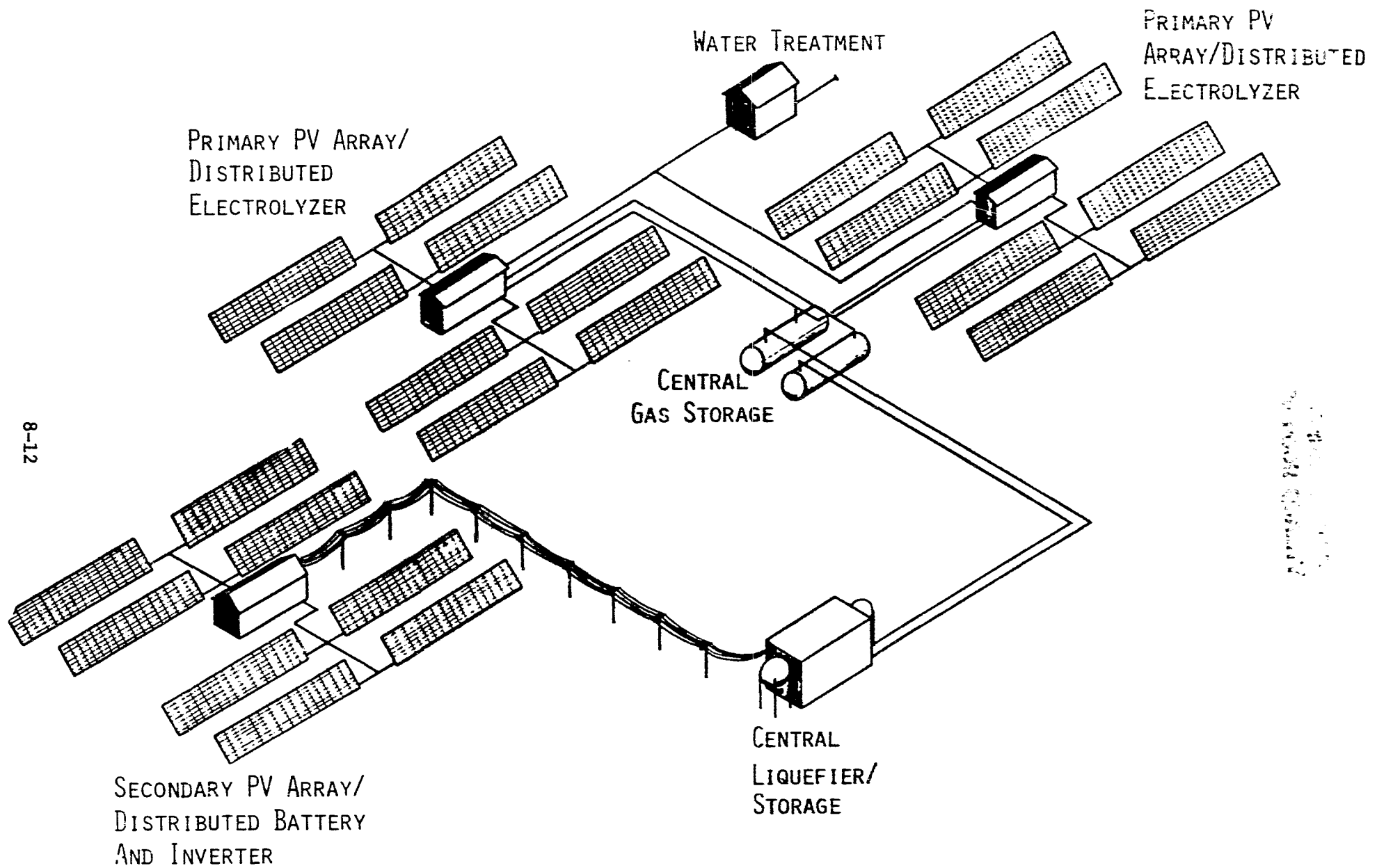
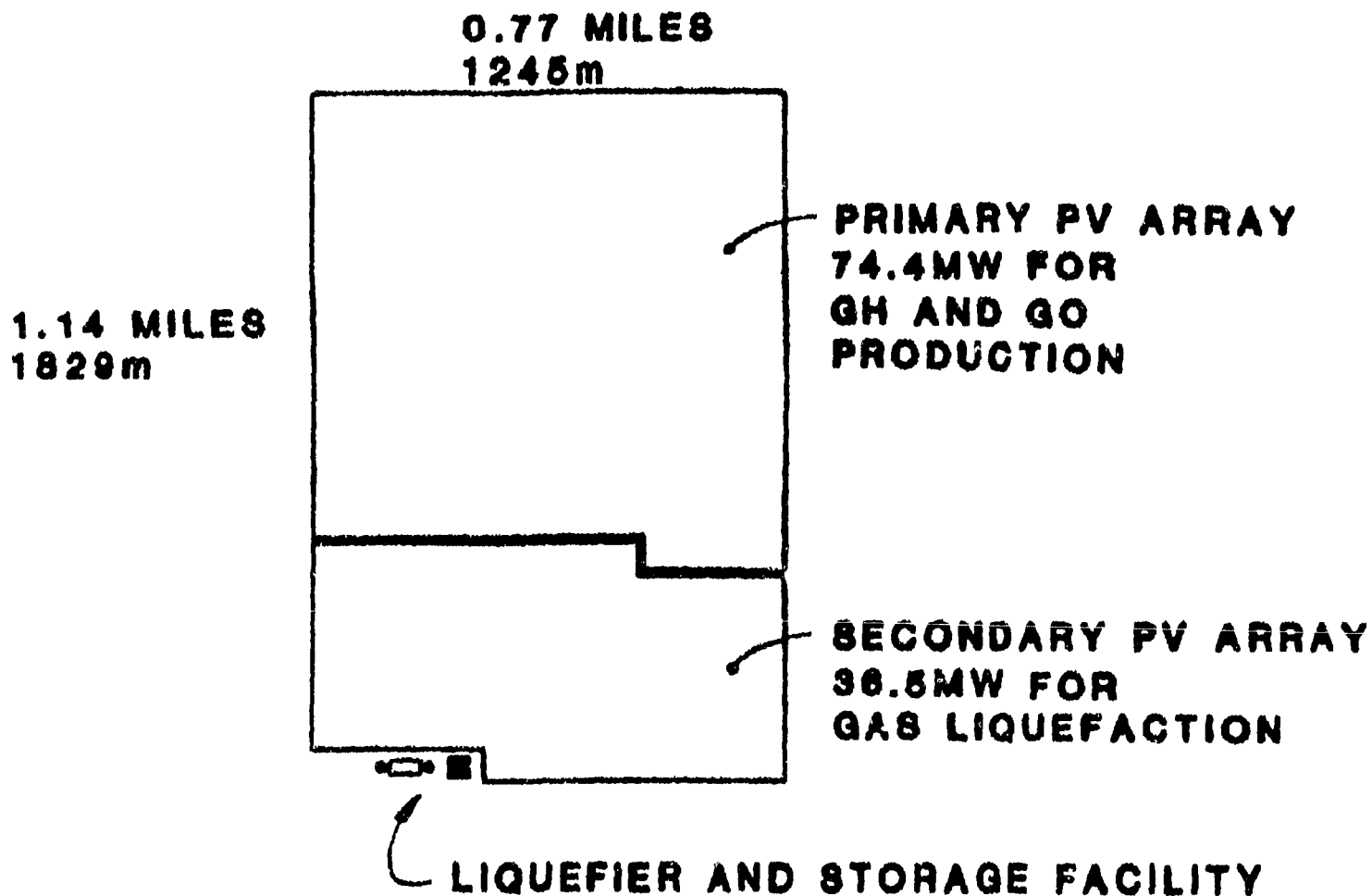


Figure 8-7. PHOTOVOLTAIC SYSTEM



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**TOTAL GROSS AREA = 0.88 SQ. MILES**

Figure 8-8. PHOTOVOLTAIC SYSTEM

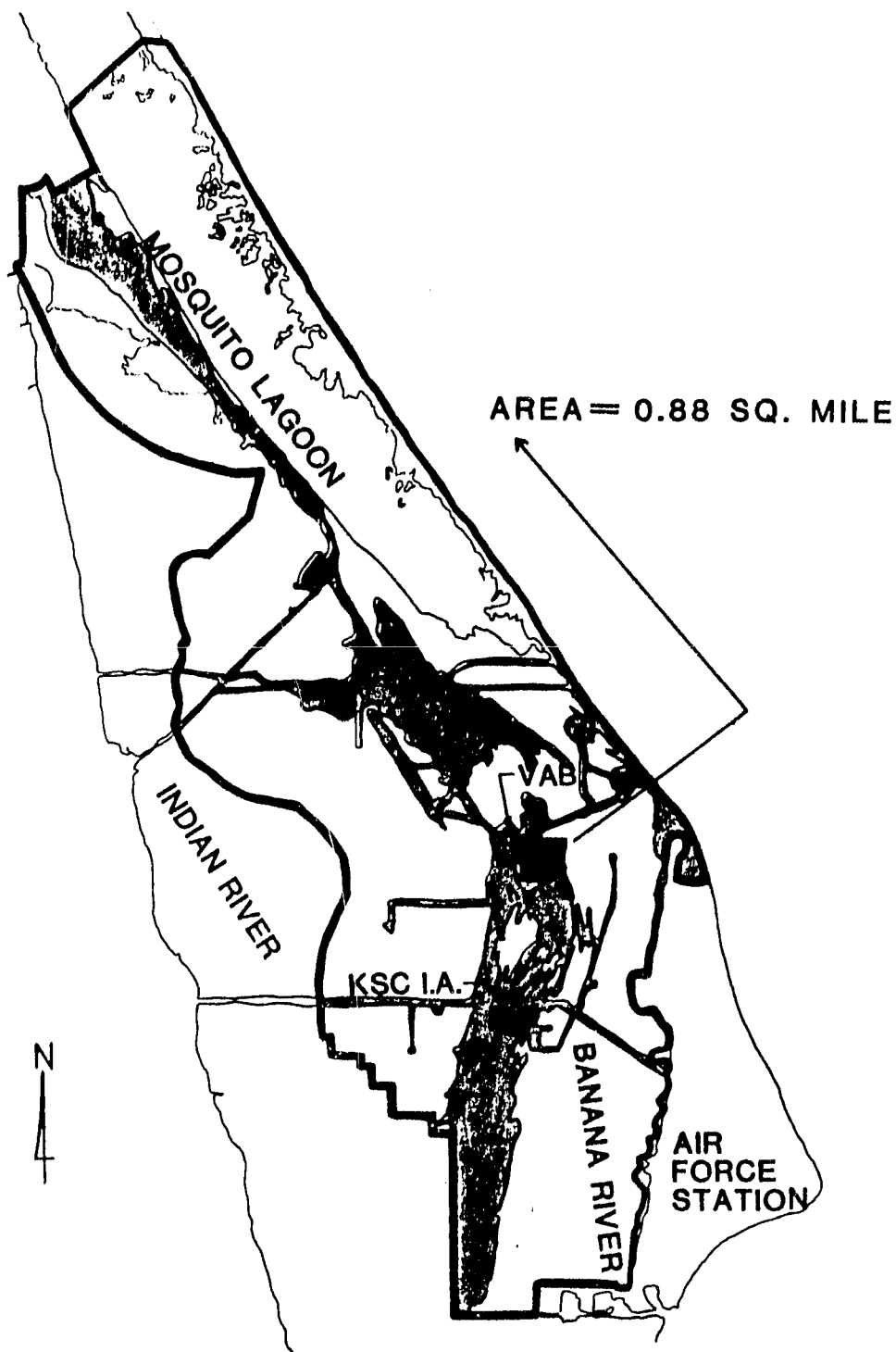


Figure 8-9. PHOTOVOLTAIC SYSTEM

subsystem. Allowing 5% for AC to DC power conditioning losses at the assumed central electrolyzer facility, the daily energy input requirement is 570.1 MWhr/day, which translates to  $208.1 \times 10^6$  kWhr/year total a.c. power.

#### Insolation Required

The average values for direct (specular, as required in concentrating systems) insolation for each month from 1977 through 1982 as measured by FSEC are shown in Figure 8-10. The 1980 data (plotted as 0) appears to be a good choice to represent a typical year. The average daily direct insolation in 1980 is only 1.1% below the 6-year daily average.

#### Tower Efficiencies

In a Power Tower system, losses occur due to numerous factors (Figure 8-11):

- cosine effect
- reflectivity
- shadowing and blocking
- attenuation
- interception
- field geometry
- receiver absorbtivity.

For Solar 100, a typical conversion efficiency curve from insolation to thermal energy in the tower is shown as Figure 8-12. The "waterfall" chart in Figure 8-11 shows additional factors which must be considered in converting insolation into electricity:

- piping/steam generator losses
- gross turbine efficiency
- net turbine efficiency.

#### Solar Energy Converted With KSC Insolation

The approach taken here was, figuratively, to "move" the solar resource to the Solar 100 location, or vice versa. The minor latitude shift in going from KSC to the Southwestern desert is not expected to produce significant changes in the results. What is to be investigated is the substantially lower KSC direct solar resource, which is only approximately 2/3 that of the desert site.

Using the efficiency curves in Figure 8-12 for each 10-day interval in the year (19 in all), curves for efficiency vs. time of day were generated. Half-hour values were interpolated from curves added between the original hourly value curves. The cut-off times shown in Figure 8-12 correspond to solar altitudes above the horizon of  $10^\circ$ - $13^\circ$ , where atmospheric attenuation amounts to 60% or more of the sunlight incident at the top of the atmosphere (Reference 8-6). FSEC measured 1/2 hour average integrated direct radiation values as a function of Eastern Standard Time. Using the "equation of time" (Reference 8-7), these values were converted to solar time.

Using the 1980 data, a numerical integral of radiation incident at the earth's surface (FSEC data), modified by the capture-efficiency (Solar 100

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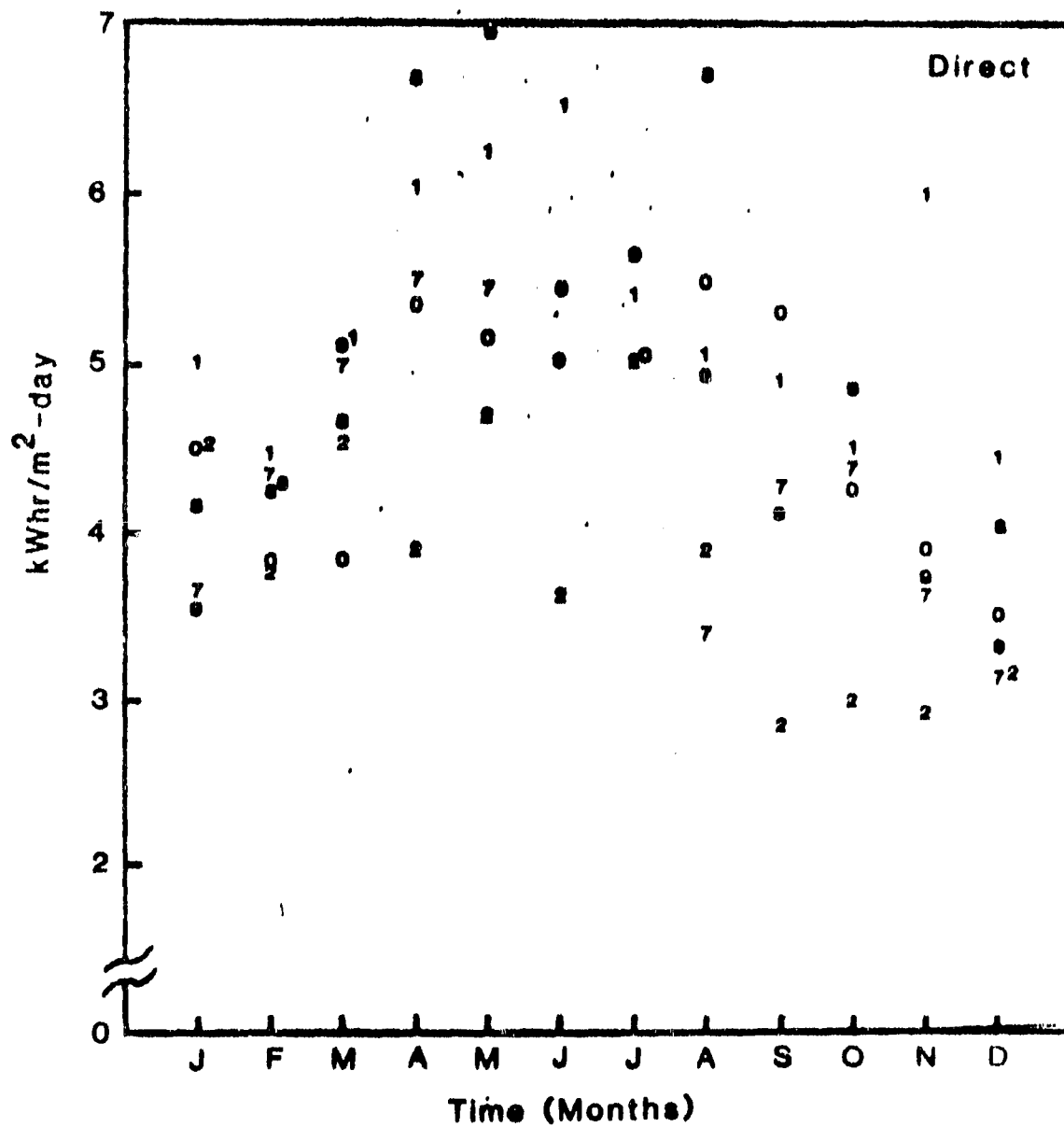


Figure 8-10. FSEC OBSERVED INSOLATION, 1977-1982

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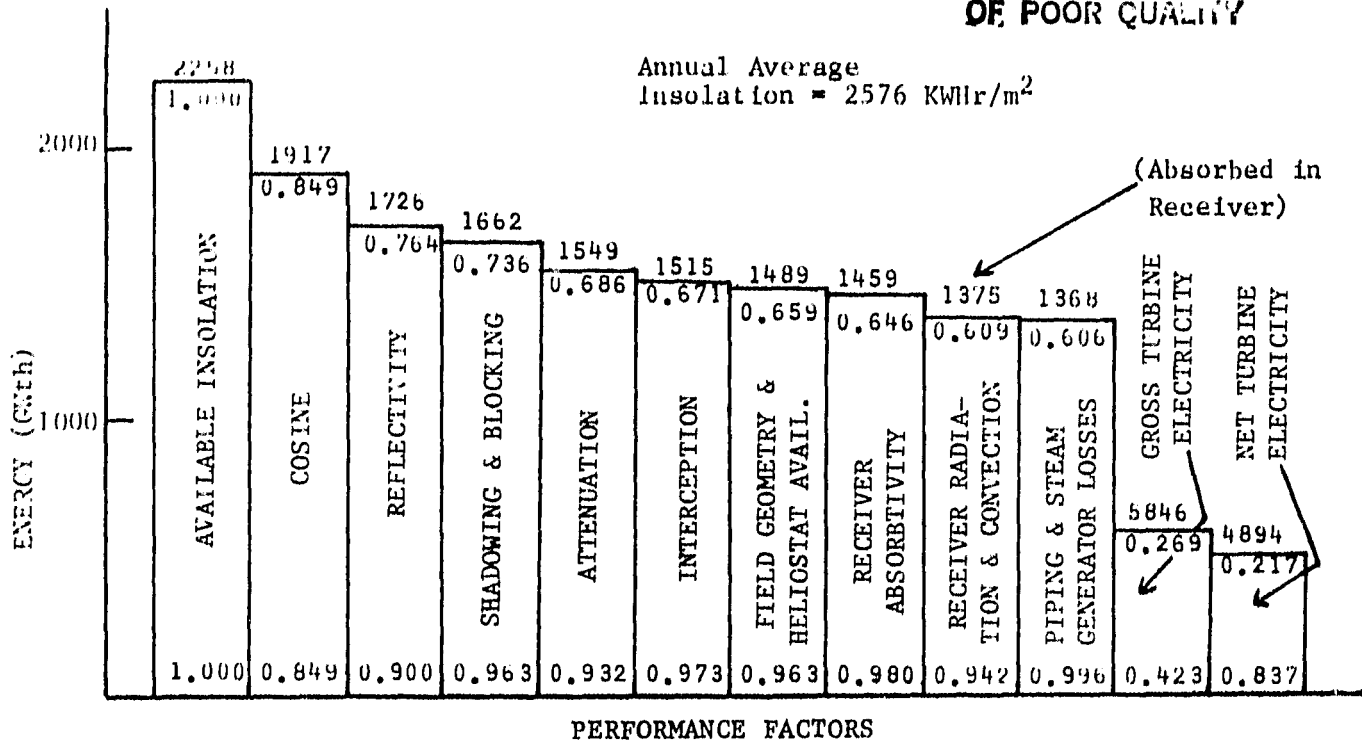


Figure 8-11. ANNUAL AVERAGE PERFORMANCE

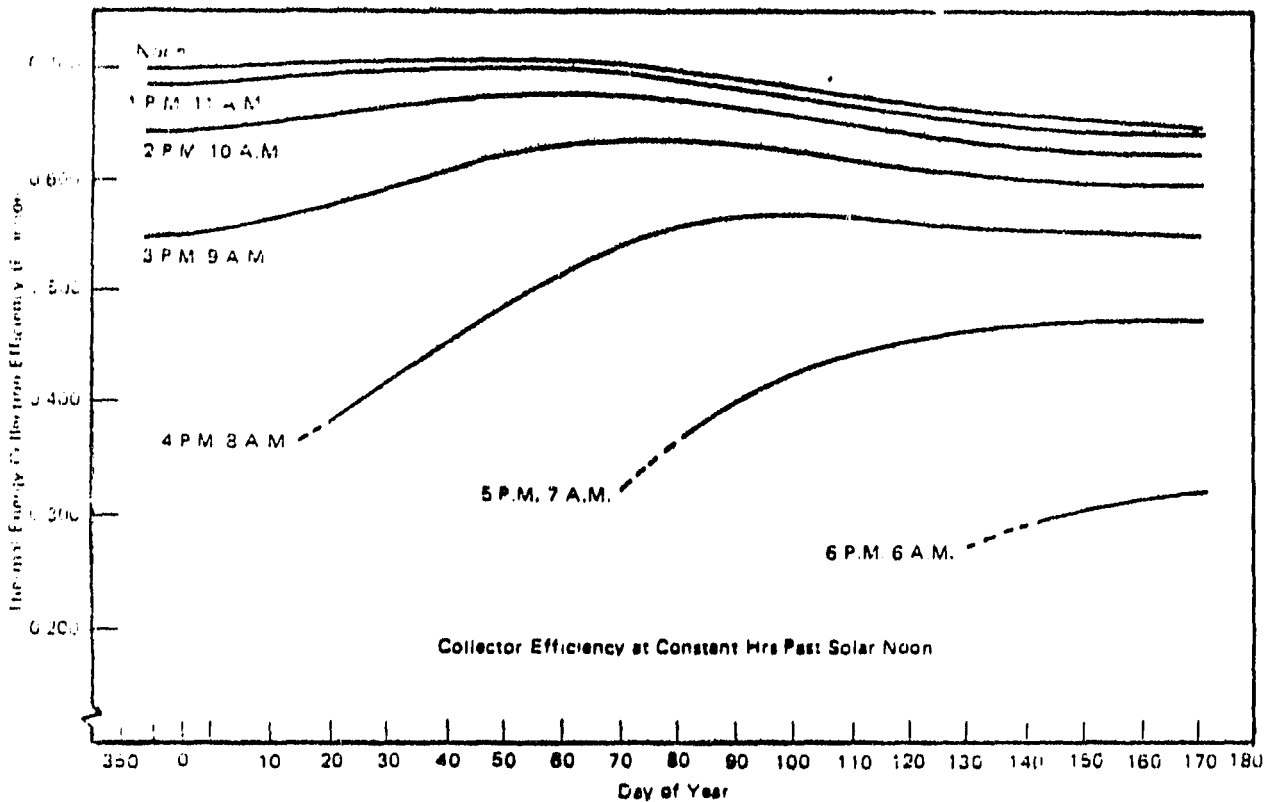


Figure 8-12. CONVERSION EFFICIENCY FROM INSOLATION TO THERMAL ENERGY

curves as fitted) was performed. The spread of daily values of energy at the collector is shown in Figure 8-13. The yearly value for one square meter of heliostat collector (corrected for 16 days of missing data) is  $1.11 \times 10^6$  kWhr/m<sup>2</sup> year at the central receiver. For comparison, the KSC-site insolation uncorrected for collection efficiency is  $1.714 \times 10^6$  kWhr/m<sup>2</sup> year compared to the desert-site value of  $2.576 \times 10^6$  kWhr/m<sup>2</sup> year.

A histogram of the number of days with stated net thermal energy at the collector vs. energy value is shown in Figure 8-14. The overall Power Tower collection system is assumed inoperative below 20% of peak power. Note that there are 60 days below an average of 1 kWt/m<sup>2</sup> day in the 1980 FSEC data. On such days, the system would not generate usable power and would resort to a self-heating mode to keep the salt molten.

Figure 8-15 shows the monthly variation. "Gross" means measured direct insolation and "net" indicates energy collectible at the receiver. Note that except for December, the "net" curve is relatively flat.

In the Solar 100 design, each heliostat has a reflective area of 57 m<sup>2</sup> so each can contribute 63.27 MWhr/year of energy to the central receiver. Correcting this for piping losses and turbine efficiencies yields 22.57 MWhr/year from each heliostat. One field of 7,712 heliostats with one central receiver tower then is capable of producing  $174 \times 10^6$  kWhr/year gross electrical output. This number must be corrected for plant auxiliary loads, i.e., pumps, heliostat drives, trace and panel heaters, etc., nominally using 1/2 the Solar 100 design (one, rather than two fields) number as representative for this analysis-- $31 \times 10^6$  kWhr/year value was obtained. Due to the lower insolation, pumping requirements will be lower, but heating requirements to keep the salt molten will be higher for the KSC location.

The net output from one field and tower is then  $143 \times 10^6$  kWhr/year. In order to meet the KSC load of  $208.1 \times 10^6$  kWhr/year, one Solar 100 type collection field, scaled up a factor of 1.455, is required. Alternatively, a two-field design with each field scaled down to .73 of the original desert design would work. Including plant auxiliary loads, the annual net electrical load produced from the turbine generator is  $253 \times 10^6$  kWhr/year, which can be met with a 28.9 MW unit operating 8,760 hours/year.

#### Power Tower-Based System Design

In contrast to the PV-based system as shown in the functional schematic illustration of Figure 8-16, the centrally-generated power feature calls for a corresponding centralized electrolyzer subsystem. This latter includes typical transformer-rectifier power conditioning equipment since AC power is assumed.

The alternatives of direct DC generation were not examined, although this approach is of potential interest since the costs and efficiency-loss related to power conditioning might be avoided. An obvious candidate approach is shaftpower-driven DC generators, both conventional and unconventional (e.g., acyclic). Also, the liquid metal MHD approach could well fit in this role with potential promise or reduced capital costs and higher efficiencies (see Appendix A for a discussion of technology status).

# ORDER OF FOCUS

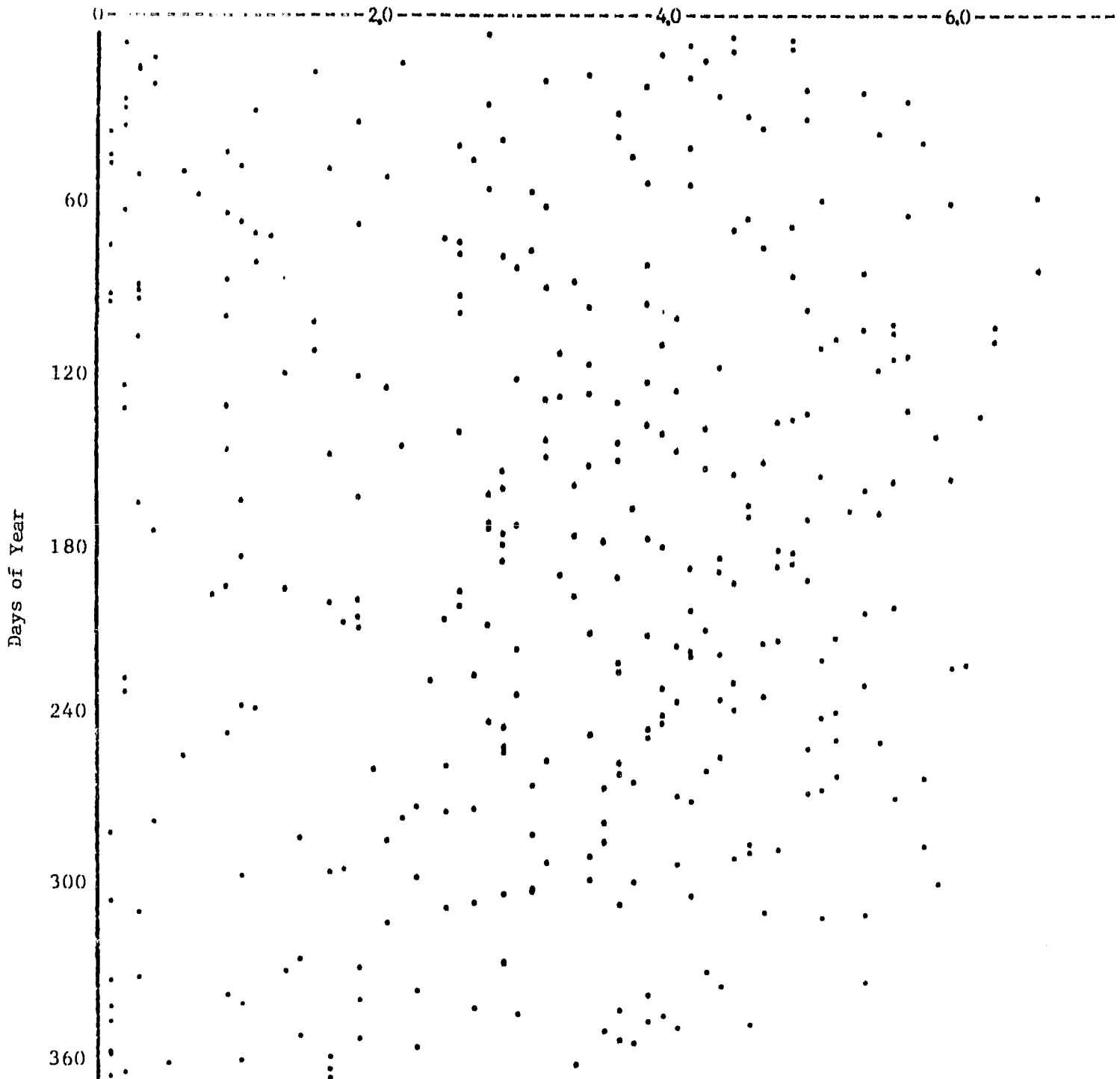


Figure 8-13. 1980 DAILY THERMAL ENERGY AT COLLECTOR (FSEC DATA) (kWh/m<sup>2</sup> day)

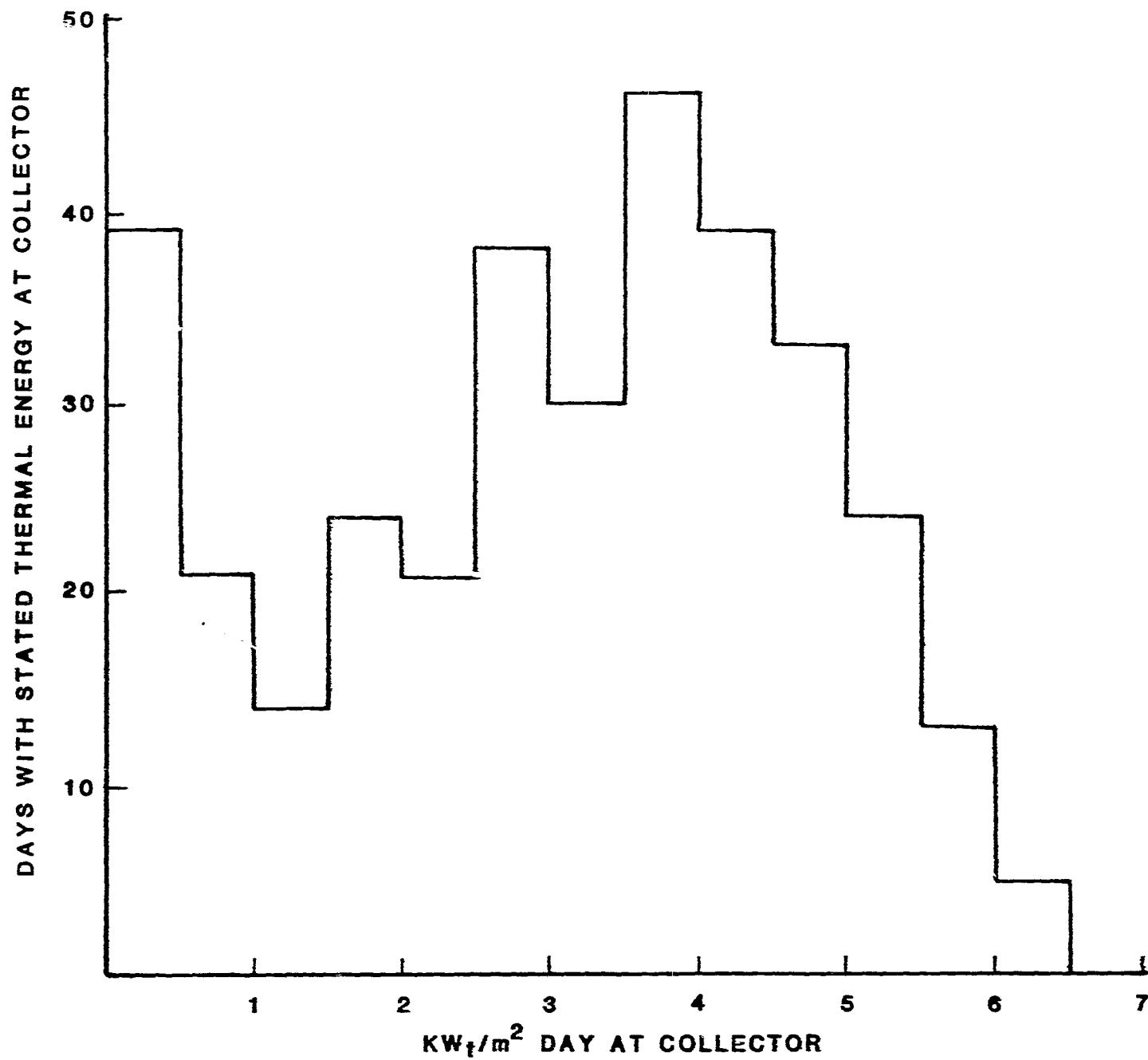
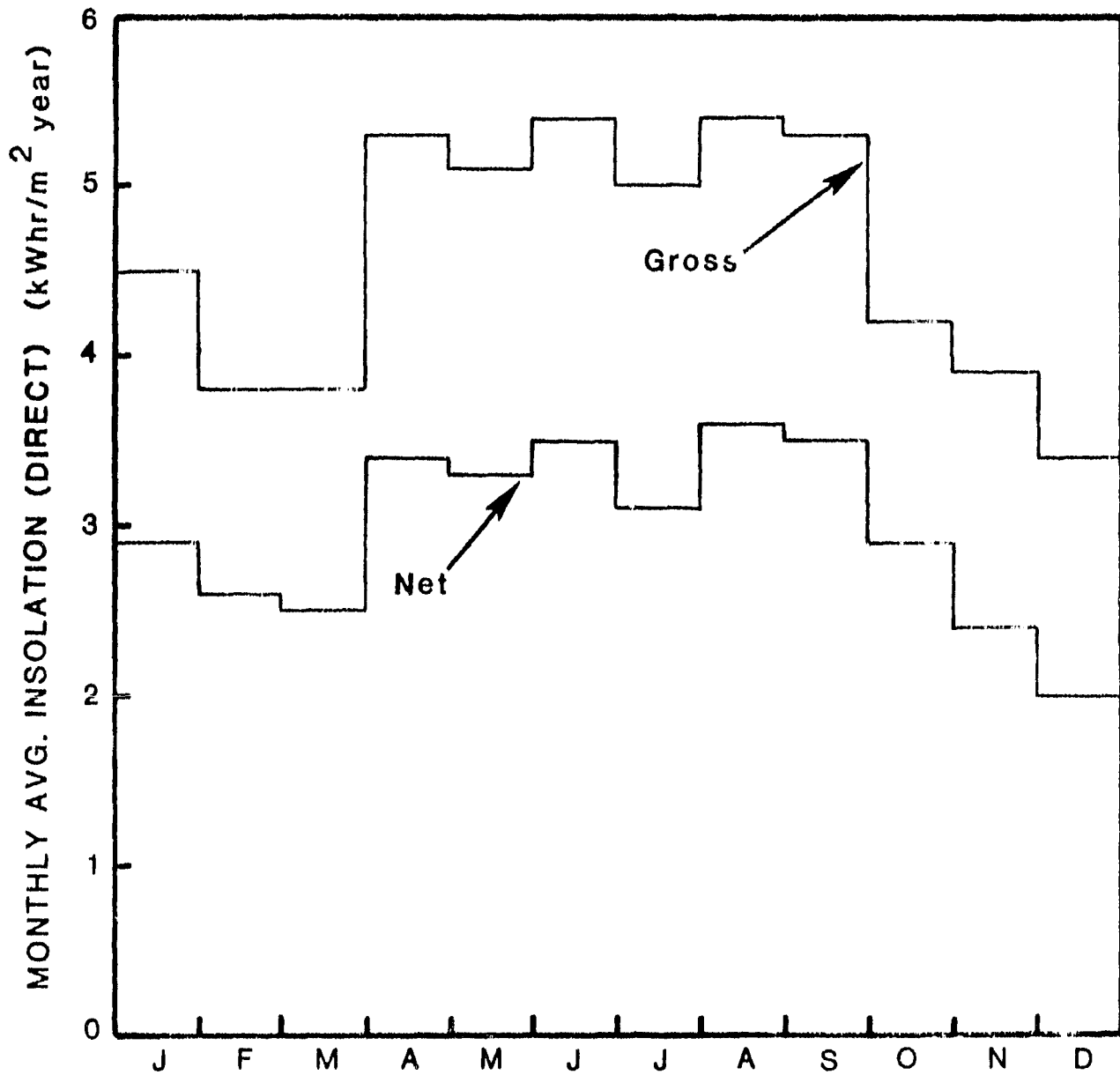


Figure 8-14. NUMBER OF DAYS WITH STATED NET THERMAL ENERGY AT THE COLLECTOR VS. ENERGY VALUE





1980 FSEC DATA, RECEIVED SUNLIGHT &  
THERMAL ENERGY AT COLLECTOR

Figure 8-15. VARIATION IN DIRECT SOLAR RADIATION FOR A "TYPICAL" YEAR

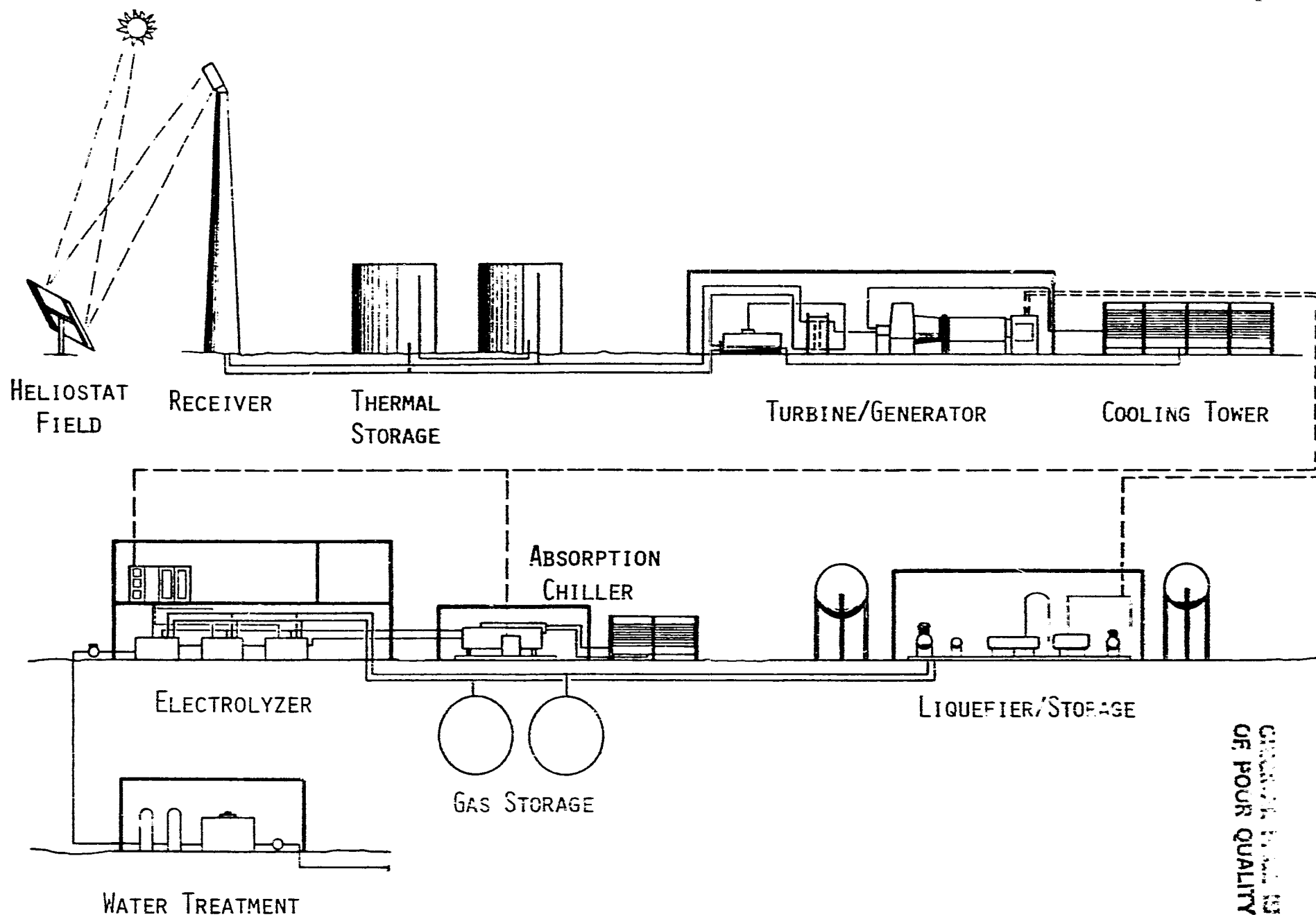


Figure 8-16. SOLAR THERMAL CENTRAL RECEIVER SYSTEM

A representative central electrolyzer installation is presented in the perspective layout sketch of Figure 8-17, showing a unipolar (tank) installation as pursued by Electrolyser, Inc., of Canada. The discussed power conditioning equipment is shown in the left foreground and the series-installed unipolar cells can be seen connected by large copper buses.

Figure 8-18 is a simplified view of the overall installation showing the key subsystems, the heliostat field, thermal storage, turbine-generator, central electrolyzer with feedstock water treatment and short-term product gas storage, and finally product liquefaction and storage.

The fact that, as in the case of the PV-based system, the solar collection component is physically dominant is brought out in Figure 8-19. As discussed, the circular heliostat field/single tower configuration corresponds to "half a Solar 100," although the field area is upsized by a factor of 1.455 as stated earlier.

Finally, for overall perspective in the sense of "physical fit" at KSC, Figure 8-20 presents a nominal siting view. Here, the installation is shown located near the VAB.

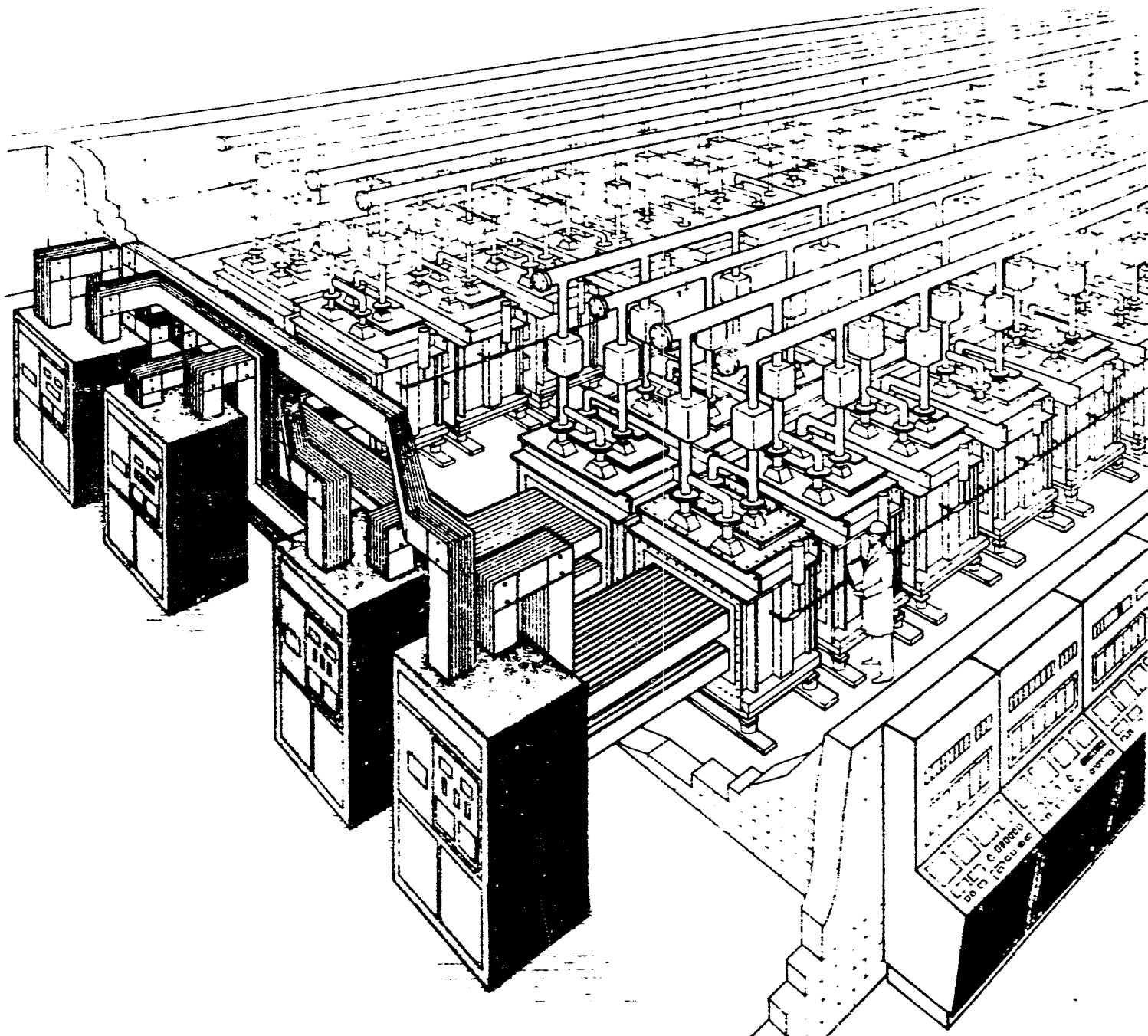
#### Power Tower System Costs

Based on costs shown (Reference 8-5), and considering that the KSC requirements are for 0.73 the solar components, 1/2 the thermal storage and 1/3 the electrical generation capability of the larger Solar 100 model, the costs from heliostats to a.c. power are:

	Capital ( $10^6$ \$)
Collector/Receiver/Tower	150.7
Thermal Storage	26.2
Steam Generator/Turbine Generator	7.8
Plant Master Control	4.0
Balance of Plant	11.9
Switchyard/Transmission	1.2
TOTAL	201.8

Annual O&M expenses were estimated at  $\$4 \times 10^6$  for this scaled down implementation. Gas storage, liquid storage, and liquefier costs are the same as for the PV system. The electrolyzers in this case are operated 24 hours/day, so only 15 MW is needed, which at  $\$220/\text{kW}$  installed including rectifier comes to  $\$3.3 \times 10^6$ . The complete cost breakdown for the power tower system to LH2 including storage is then:

	Capital ( $10^6$ \$)	O&M
Entire Solar-Energy Conversion System (Heliostats through Elec. Generation)	201.8 (126.5)	4.00
Electrolyzer	3.3	0.066
Gas Storage	9.2	0.092
Liquefier	14.8	0.76
Liquid Storage	3.6	0.036
TOTAL	232.7 (157.4)	4.954



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Figure 8-17. LARGE CENTRALIZED WATER ELECTROLYZER  
(Source: Electrolyser, Inc.)

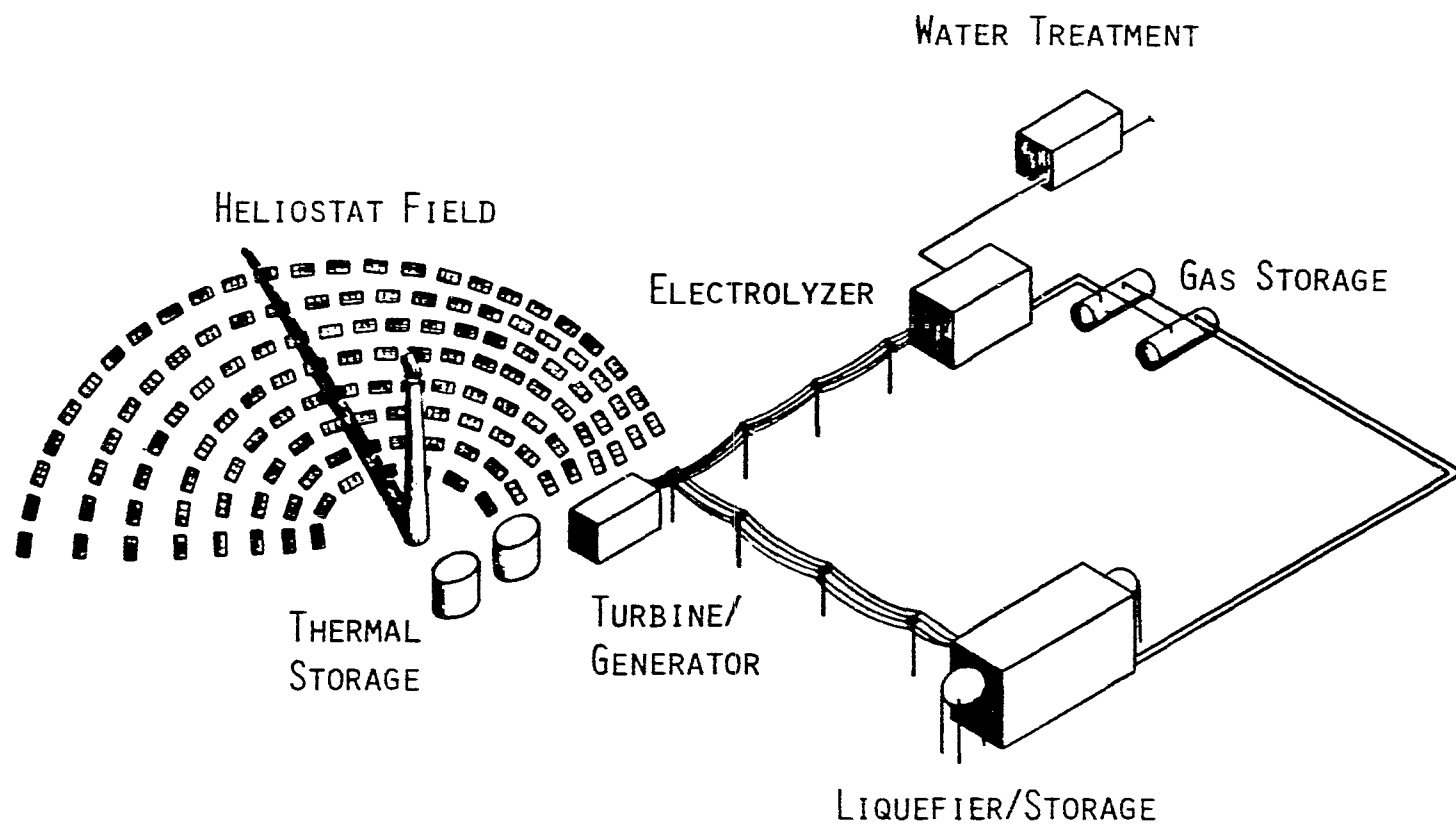


Figure 8-18. SOLAR THERMAL CENTRAL RECEIVER SYSTEM

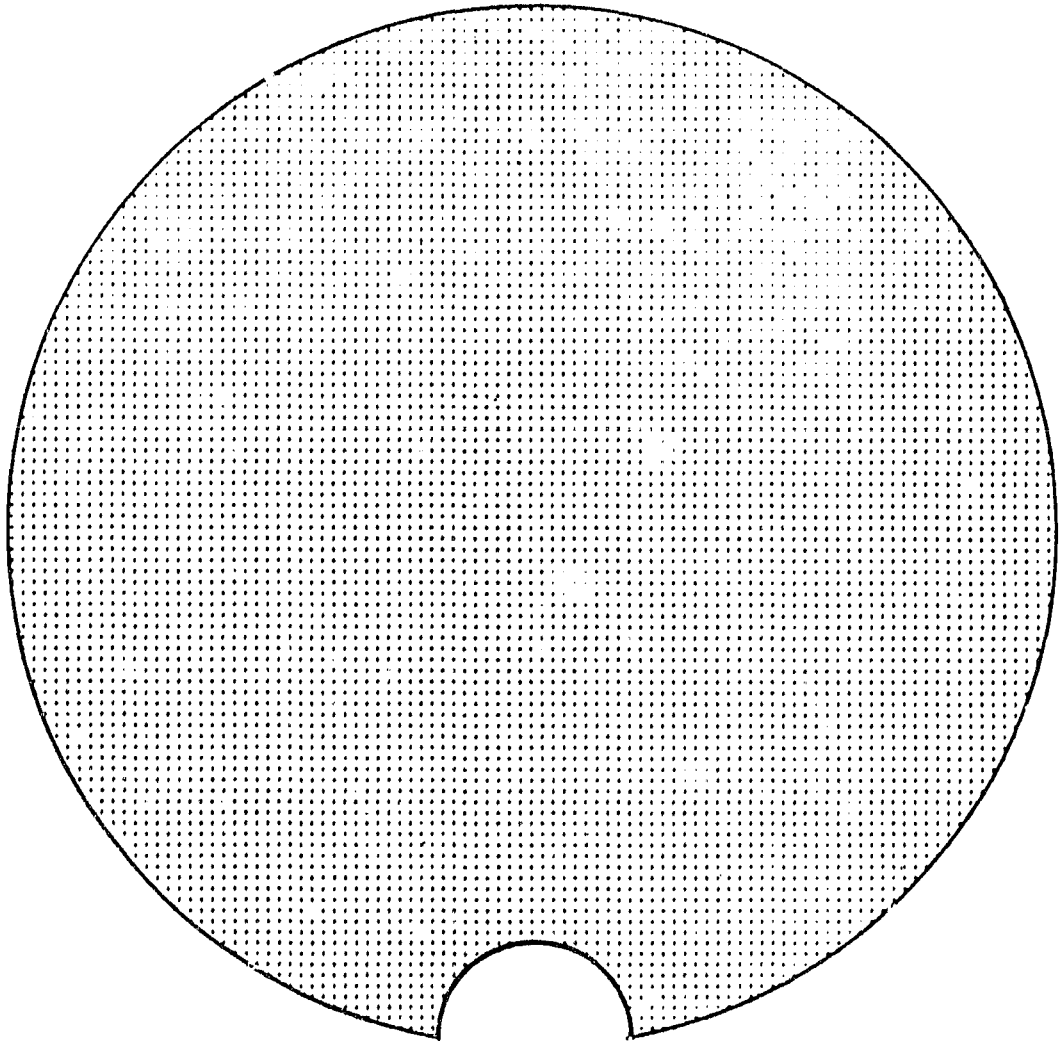
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## HELIOSTAT FIELD

AREA =

0.90 SQ. MILE

DIA. = 1.10 MILE



RECEIVER TOWER

HEIGHT : 760-800 FT.



Figure 8-19. SOLAR THERMAL CENTRAL RECEIVER SYSTEM

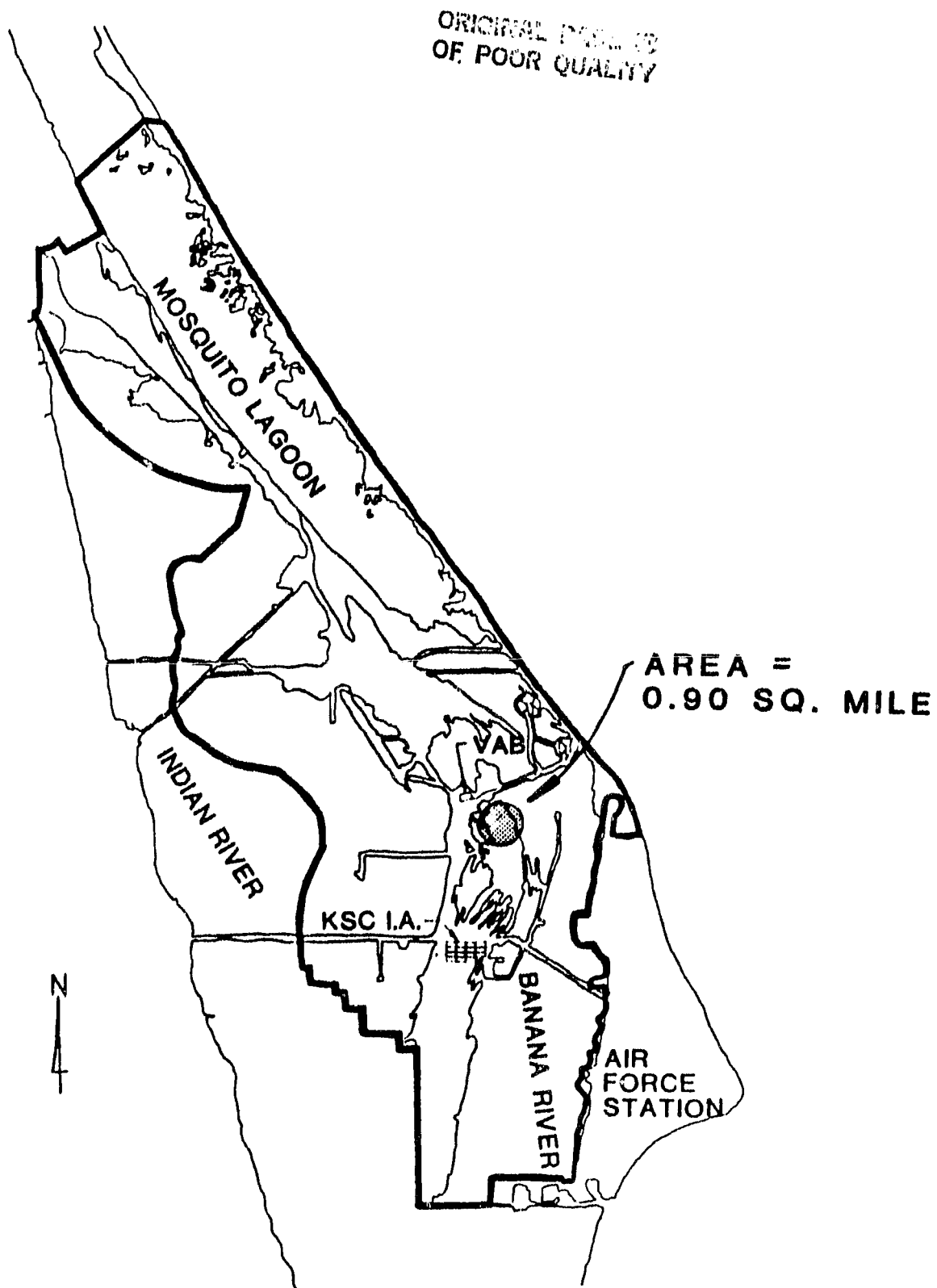


Figure 8-20. CENTRAL RECEIVER SYSTEM

It is estimated that if a significant number of power tower systems are eventually constructed, the solar components (first item in list) could be reduced in cost by a factor of as much as 2 (Reference 8-8). This is the basis for the numbers in parentheses above, which may be taken as more optimistic future costs. The ramifications to liquid hydrogen product costs are covered in following sections.

## Estimated PV- and PT-Based Systems and Reference Liquid Hydrogen Product Costs

### General Approach

Using the capital, operating and maintenance, and other input (i.e., electricity) costs presented earlier for the two "finalist" systems, estimated liquid hydrogen and liquid oxygen (coproduct) costs are developed in this section. In the next-following section, certain reference comparison costs are developed to provide a basis of judgment for the non-fossil energy-based systems. All costs are then compared on both a dollar and a normalized (to comparison cases) basis to complete this section of the report.

### Costing Methodology

As in the cost-based second screening activity reported in Section 7, the same cost estimation methodology is used in evaluating these PV- and PT-based systems. In review, this is based on the EPRI TAG estimation procedure (Reference 7-1) using (early) 1983 dollars. The following financial assumptions, corresponding to typical "industrial financing rules," are used:

- |                       |                             |
|-----------------------|-----------------------------|
| • 6% inflation        | • 2% property tax/insurance |
| • 50% debt/50% equity | • 10% investment tax credit |
| • 12% discount rate   | • 10-year depreciation      |
| • 48% income tax rate | • 20-year book life.        |

The TAG model provides 20-year levelized costs of product taken, nominally, over the period: 1990-2010. Again, first-quarter 1983 dollars are used throughout.

For energy-input-related expenses, particularly for electricity and natural gas, an escalation-above-inflation factor is used. Mainly affected are the comparison reference cases: (1) conventional (present) supply by steam-reforming of natural gas and (2) utility-electricity operated on-site electrolyzer/liquefier system. Such escalation is taken over the range of 1%-5% per year with 3% representing the nominal case. This percentage is applied to the total cost (not just the energy-input cost contribution) in the cases affected, as will be seen.

### Liquid Oxygen Coproduct Cost Crediting Approach

As discussed earlier, in view of the fact that water electrolysis intrinsically provides oxygen coproduct, along with hydrogen product, the additional step of liquefying the oxygen for KSC use is taken. As fueled, rocket systems such as the Space Shuttle use liquid hydrogen and oxygen at about an oxygen-to-hydrogen mass ratio of 6. With the stoichiometric ratio being 8 (i.e., from the basic water-splitting reaction), and with hydrogen losses in storage and transfer, etc., being relatively higher than that for



oxygen, this suggests more liquid oxygen than required is to be produced. On the other hand, KSC currently launches expendible space vehicles which use liquid oxygen, but other than liquid hydrogen fuel. This tends to counter the "surplus liquid oxygen" situation. However, with the future stress placed on hydrogen/oxygen-powered vehicles, compounded by the planned phase-out of these expendible vehicles (Atlantia-Centaur, Delta), this compensating factor is likely small.

Nevertheless, for coproduct crediting purposes, it was assumed that all the liquid oxygen produced is taken by KSC (which, in principle, could "market" the surplus elsewhere). The cost basis used was KSC's current estimated cost of industrially-supplied liquid oxygen of \$.036/lb. To place this cost in equitable terms, it was escalated at 3% and, using the TAG routine, this equates to a levelized 20-year cost of \$.075/lb. Since 8 pounds of oxygen accompany 1 pound of hydrogen, as a coproduct credit in terms of liquid hydrogen cost-offset, this amounts to \$.60/lb LH<sub>2</sub> (i.e., 8 x \$.075).

#### PV-Based System Levelized Liquid Hydrogen Costs

For the stand-alone PV-based system described, liquid hydrogen costs are dominated by the installed PV-module capital costs (e.g., as shown in Appendix D). Hence, hydrogen costs were calculated over a range of assumed module costs. Judgmentally, this cost-range was cast in an "optimistic" vein of from \$.50 to \$2.00/Wp (installed). This fact can be clearly seen if the trends of Figure 8-1 are examined; recall these latter are on an uninstalled basis. The basic stand-alone, PV-based system levelized (1990-2010) costs in early-1983 dollars, including the liquid oxygen coproduct credit, are:

Stand-Alone Basis	
<u>PV Installed Costs</u>	<u>Liquid Hydrogen Cost</u>
(\$/Wp)	(\$/lb)
.50	2.96
1.00	4.40
2.00	7.30

A variant of the system, in which the liquefier was powered directly by electric utility-supplied electricity, was examined. Although, in a sense, this somewhat violates the "non-fossil" nature of the system, it allowed for the deletion of major expense items, e.g., auxiliary PV field, batteries, inverters. Two assumed nominal electric rates were used parametrically: \$.03 and \$.06/kWhr. Although no "official" rates could be stated by the Florida Power and Light Company (FPL), discussions with company technical representatives were taken into account in choosing this range of costs.

#### Utility-Powered Liquefier

<u>PV Installed Costs</u>	Liquid Hydrogen Costs at	
	<u>Stated Utility Electricity Costs</u>	
	<u>\$.03/kWhr</u>	<u>\$.06/kWhr</u>
.50	2.53	3.04
1.00	3.51	4.02
2.00	5.48	6.00

### PT-Based System Levelized Liquid Hydrogen Costs

Two hydrogen costs were calculated for the power tower-based system detailed above. These corresponded to taking the directly-related solar energy conversion equipment (e.g., heliostats, central receiver tower) capital costs at two levels: (1) as assumed in the Solar 100 study and (2) 50% of these costs (see previous details). In this, the non-solar equipment (e.g., turbine-generator, electrolyzer, liquefier) was held at the single set of costs stated. On this basis, the basic stand-alone PT-based system levelized (1990-2010) costs in early-1983 dollars with the coproduct credit are:

<u>PT-System Case</u>	<u>Liquid Hydrogen Cost (\$/lb)</u>
(with 50% reduction in Solar equipment)	4.77
Nominal Case	6.70

### Reference Comparison Cases

#### Conventional Steam-Reformed Natural Gas Industrially-Provided Liquid Hydrogen

Using a current estimated cost of liquid hydrogen delivered to KSC from the Air Products and Chemicals, Inc., 60-ton/day New Orleans, LA, facility of \$2.73/lb (Reference 8-9), an equivalent set of 1990-2010 levelized costs were developed. The key parameter was the amount of escalation assumed, this being a highly energy-related production process, viz., natural gas and electricity. The range of escalation was 1%-5%, with 3% assumed as the "nominal" estimate.

<u>Assumed Escalation Over Inflation</u>	<u>Liquid Hydrogen Costs (\$/lb)</u>
1%	4.69
3%	<u>5.63</u>
5%	6.82

#### Utility-Powered Electrolyzer/Liquefier Facility (No Solar-Energy Conversion)

In this final comparison case, the situation of directly planning the electrolyzer and liquefier subsystems with utility-provided electricity was examined. Round-the-clock operation was assumed, obviously without stand-alone capability. The same cost of electricity ranges as used in the PV-case variant were used. These costs were escalated at 3% and the coproduct credit then taken.

<u>Assumed Average Utility Electricity Costs</u>	<u>Liquid Hydrogen Costs (\$/lb)</u>
\$.03/kWhr	2.42
\$.06/kWhr	4.41

## Cost Comparison Summary

Levelized liquid hydrogen costs\* were obtained for the nominal 20-year period 1990-2010 using the EPRI TAG model for the two finalist systems-- Photovoltaic (PV) and Power Tower (PT). These are shown in Table 8-1, together with two comparison cases and comparative cost ratios. The ratios reflect relative costs under the financial assumptions used, and are more reliable than absolute product costs. Both the PV and PT systems are presented for solar apparatus costs which bracket those anticipated in 1990.

The conventional baseline system, the first comparison case, is derived by taking today's delivered product cost based on natural gas steam reformation and levelizing over a 20-year period with various (1%, 3%, or 5%) escalators over the assumed inflation rate (6%) to reflect the energy intensiveness of obtaining the product conventionally.

The utility power-based system, the second comparison case, consists of electrolyzer and liquefier subsystems at KSC operated 24 hours/day for assumed 1983 power costs of \$.03 and \$.06/kWhr. These costs are also levelized.

For the PV system, a variant using utility power (at the above two rates) to operate the liquefier was also estimated. This system retains only the primary PV array with distributed electrolyzers to produce the hydrogen and oxygen product gases. Liquefaction takes place around the clock using purchased electricity.

The resulting sets of comparison ratios are provided at the right of Table 8-1, one using the estimated levelized cost using today's method as the reference, the other using a utility-powered system as the reference.

It is apparent that with sharp price reductions for the solar-based systems, as an expectation, that product costs comparable to the conventional may be possible in the 1990-2010 period. Further, the utility-based system appears to offer the lowest anticipated cost relying, however, in part on fossil resources in the case of the Florida Power and Light Company, within whose service area KSC lies.

In summary, as reflected in Table 8-1's right-hand columns (reference cases are emphasized):

- PV-system costs range from about 60% to 130% and PT-system costs are 85% to 120% of the conventional reference case (at 3% escalation)
- PV-system costs are estimated from about 80% to 165% and PT-system costs are 110% to 150% of the utility reference case.

---

\* Levelized costs can be viewed as long-term average product costs in essentially current 1983 dollars.

Table 8-1. SUMMARY OF LEVELIZED LH<sub>2</sub> COSTS (1990-2010)

NOTE: Escalation on Energy Costs 3% Unless Otherwise Noted

<u>\$/lb LH<sub>2</sub></u>		<u>Conventional Baseline Systems</u>	<u>Nominal Ratios</u>			
			<u>"Conventional"</u>	<u>"Utility"</u>		
4.69		1% Escalation	.83	1.06		
5.63		3% Escalation	<div>1.00</div>	1.28		
6.82		5% Escalation	1.21	1.55		
<u>\$2/Wp</u>	<u>\$1/Wp</u>	<u>PV-Based Systems</u>	<u>\$2/Wp</u>	<u>\$1/Wp</u>	<u>\$2/Wp</u>	<u>\$1/Wp</u>
7.30	4.40	Stand-Alone (No Utility)	1.30	.78	1.66	1.00
5.48	3.51	Utility-Powered Liquefier at \$.03/kWh	.97	.62	1.24	.80
6.00	4.02	Utility-Powered Liquefier at \$.06/kWh	1.07	.71	1.36	.91
		<u>Power Tower-Based Systems</u>				
6.70		Nominal Case	1.19		1.52	
4.77		Reduced-Cost Case (50% as noted)	.85		1.08	
		<u>Utility Power-Based Systems</u>				
2.42		Average Power at \$.03/kWh (3% Escalation)	.43		.55	
4.41		Average Power at \$.06/kWh (3% Escalation)	.78		<div>1.00</div>	

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## 9. TECHNOLOGY TRACKING

### Objective of Technology Tracking

A principal objective of this project has been to provide information to support management decision-making regarding non-fossil liquid hydrogen production possibilities. This is an element in planning and selecting means to meet STS (e.g., Space Shuttle) and other KSC liquid hydrogen requirements in the future. Three options are currently of interest and/or under preliminary investigation: continuation of the present natural gas-based system, the use of coal-based cogeneration production systems ("Polygeneration" concept), and that alternative addressed in the present study--non-fossil hydrogen production.

The nature of any future decisions is obviously significantly dependent upon the potential benefits to be derived from any "new" hydrogen production system vs. those provided by continuing the use of the already in-place natural gas-based industrial-supplier system. It appears quite possible that a decision to implement any such "new" system may be deferred for a considerable period of time. If this is the case, it is obvious that the technologies and systems studied herein will, as a rule, advance in R&D status during that time period. Some of the alternatives may have even moved into demonstration and early deployment stages.

Thus, the objective of this section is to provide background and recommendations covering technological tracking activities in related fields to be carried out over what may be a significant period of time.

### The Development of New Technologies--A General Discussion

In most cases, the evolution of a new technology can be characterized in terms of five phases. Four of these phases are illustrated in Figure 9-1. These are the conceptual development, rapid growth, consolidation, and maturation phases. The fifth phase (not shown in Figure 9-1) is the period of replacement of what was once a new technology with an even more advanced technology and the evolution of the first technology to an "old" technology with its phasing down in the marketplace.

The dynamics of this process have been a subject of rather extensive investigation. These investigations have been motivated by the consideration that market penetration analysis is an integral requirement of industrial marketing planning where technologies are involved. A recent investigation, carried out by the Electric Power Research Institute (EPRI; Reference 9-1), is recommended to the reader as providing a good overview of methods of analyzing the market penetration of end-use technologies.

Fisher and Pry further defined the "logistic" or "sigmoid" curve previously illustrated in Figure 9-1 to produce the curve shown in Figure 9-2, which defines the portion of the market penetrated vs. a function of a ratio of time periods. In plotting the actual penetration of these 17 technological product systems, a great deal of consistency was found as illustrated in Figure 9-3a and 9-3b.

One such investigation which can provide us with a better understanding of what we are discussing here was carried out by Fisher and Pry of the

# ORIGINALITY OF POOR QUALITY

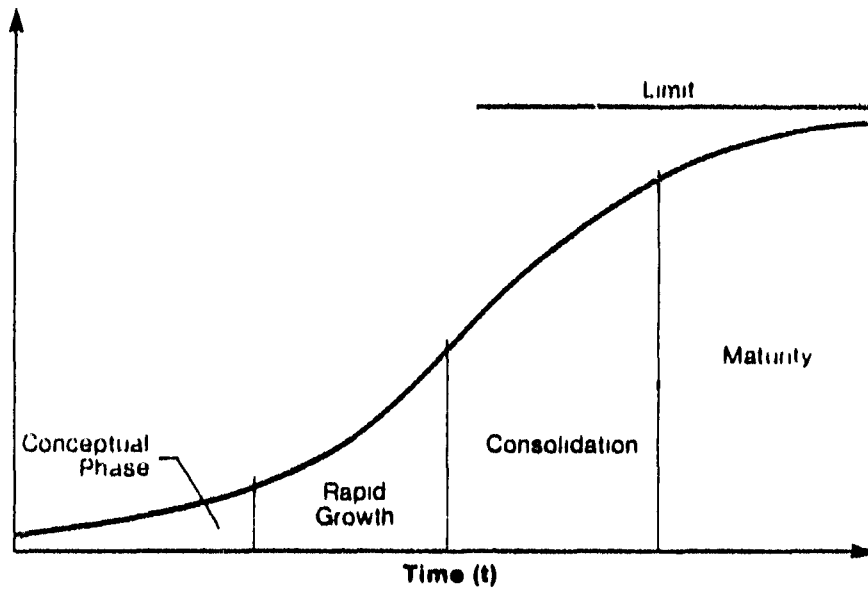


Figure 9-1. THE "LOGISTIC" OF "SIGMOID" CURVE OF THE DEVELOPMENT OF A NEW TECHNOLOGY

(Source: Hitch, C.J., ed., "Energy Conservation and Economic Growth," American Association for the Advancement of Science Selected Symposium Series, Washington, D.C., Westview Press, Boulder, CO, 1978)

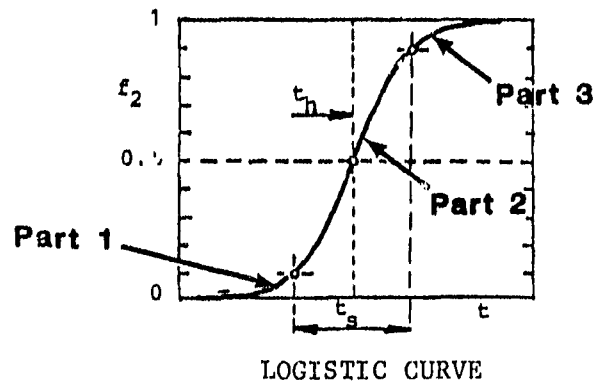
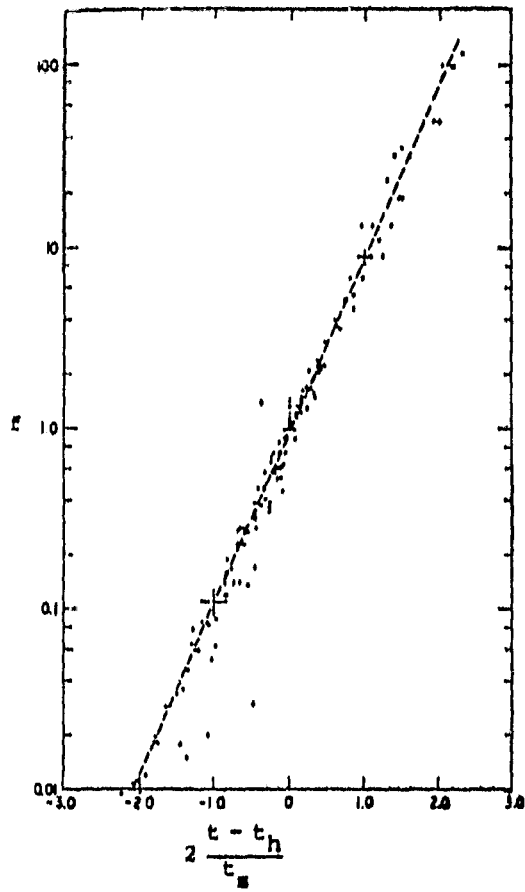
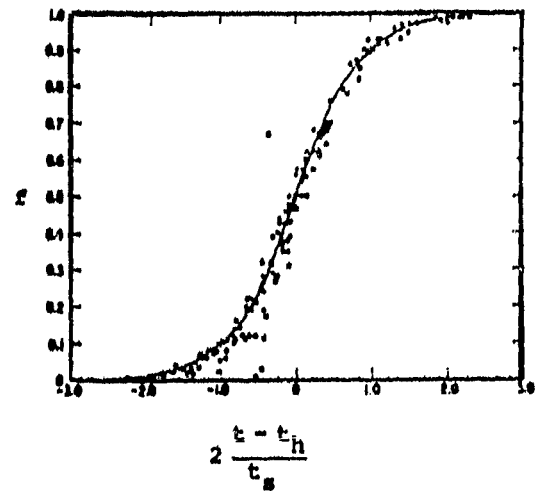


Figure 9-2. CHARACTERIZATION IN TIME AND PHASING OF THE TECHNOLOGICAL DEVELOPMENT/DEPLOYMENT PROCESS



(a)



(b)

Figures 9-3a and 9-3b. CORRELATION ANALYSIS RESULTS FOR 17 SUBSTITUTION PROCESSES



# ORIGINAL INTENT OF POOR QUALITY

General Electric Company in 1970 (Reference 9-2). Fisher and Pry investigated the 17 technological "displacements" of old products by new products listed in Table 9-1. The reader should especially note the characteristic long-term nature of development and deployment of a technology (quantity " $t_s$ " in years) as presented in this table.

Table 9-1. REPRESENTATIVE NEW TECHNOLOGY/OLD TECHNOLOGY REPLACEMENT  
CHARACTERISTIC TIMES

(NOTE: See Figures 9-1 and 9-2 and accompanying text.)

Substitution	$t_s$ Years	$t_h$ Year
Synthetic/Natural Rubber	58	1956
Synthetic/Natural Fibers	58	1969
Plastic/Natural Leather	57	1957
Margarine/Natural Butter	56	1957
Electric Arc/Open Hearth Specialty Steels	47	1947
Water-Based/Oil-Based House Paint	43	1967
Open Hearth/Bessemer Steel	42	1907
Sulfate/Tree-Tapped Turpentine	42	1959
TiO <sub>2</sub> /PbO-ZnO Paint Pigments	26	1949
Plastic/Hardwood Residence Floors	25	1966
Plastic/Other Pleasure Boat Hulls	20	1966
Organic/Inorganic Insecticides	19	1944
Synthetic/Natural Tire Fibers	17.5	1948
Plastics/Metal Cars	16	1981
BOF/Open Hearth Steels	10.5	1968
Detergent/Natural Soap (US)	8.75	1951
Detergent/Natural Soap (Japan)	8.25	1962

The work by Fisher and Pry demonstrates that once a product begins to penetrate the market, i.e., it is judged a product desired by the market and becomes subject to "market-pull" rather than "technology-push," that market penetration will proceed along a generally clearly-definable path. However, in the original reference, the authors note that this trend-methodology is often not applicable until after a product has achieved at least a 4%-5% market penetration. Thus, for the subject at hand which may be a "first up" example, we must be particularly concerned with that time period preceding that second point in time where the product begins market penetration under such market-pull influences.

The nature of this initial time period (Part 1) was studied by Battelle-Columbus Laboratories in 1973 and the general findings from this study are presented in Table 9-2 (Reference 9-3). The reader should note this mean time period of 19.2 years is the time from "first conception" to "first realization" which, in the subject study, ends (within the accuracy of such definition) with the beginning of the period of rapid growth in the market penetration rate under apparent market-pull conditions, i.e., Part 2 of the curve in Figure 9-2.

Table 9-2. TIME LAGS FROM "FIRST CONCEPTION" TO "FIRST REALIZATION" FOR NOTABLE TECHNOLOGICAL INNOVATIONS

1.	Heart Pacemaker	32 years
2.	Hybrid Corn	25 years
3.	Hybrid Small Grains	19 years
4.	Green Revolution Wheat	16 years
5.	Electrophotography	22 years
6.	Input-Output Economic Analysis	26 years
7.	Organophosphorous Insecticides	13 years
8.	Oral Contraceptives	9 years
9.	Magnetic Ferrites	22 years
10.	Video Tape Recorder	6 years

Mean Duration: 19.2 years

#### Relevance to This Study

Consistent with KSC guidance, the present study has preferentially considered systems predicated on those technologies that might be placed in operation at KSC as early as 1987. However, a decision to delay such system implementation to a time further in the future is a possibility, if not a probability. Hence, two additional time periods were considered as a basis for evaluation of the technologies under consideration. These time periods were about 1992 and 2000. Thus, the nearly two decades may elapse prior to any "technology freeze" necessity in the extreme-option case.

In order to be responsive to actually meeting these requirements at a given time of need, a successful candidate technology must be essentially fully implementable as working hardware. Put generally, the need is to design, install, operate, and maintain a product-producing system delivering that product reliably and at an acceptable cost. All prior work related to moving the technology to a commercial status (R&D, etc.) must have been completed by the time-period selected for beginning actual construction.

In recapitulation, the previous discussion should clearly demonstrate one salient point: while we may wish it were not so, historical evidence indicates that the process of developing a technology to a marketable status is a process that takes decades. For the study-purpose at hand, we can draw the following basic conclusions:

1. If the implementation date selected is 1987, any candidate technology must be fully developed and already demonstrated as a commercial-product status system.
2. If the 1992 time period is selected for the date of implementation, there is about a 5-year time period in which in-development technologies, which are not presently commercialized, can be significantly improved and during which present commercialized technologies may be further improved. This is a short but utilizable time period with the possibility of concomitant significant advances.
3. If the ca. 2000 time frame is selected for the time of implementation, the possibility of using presently "emergent" technologies with their technoeconomic advantages must be considered.

We can also conclude from previous discussions that the tracking of non-fossil hydrogen related technologies during the ensuing time period will not require any intensive efforts by/for KSC--the maturing of technologies is clearly not a "fast-paced" process. In fact, it would appear that technology tracking is not really required if a 1987 implementation date is selected; in-commercialization hardware only will be applicable. Technology tracking becomes increasingly important, however, as later implementation dates are considered. On the other hand, then, the time available for such continuing assessment is then available.

#### Breakthroughs - Step-Function Technological Advances

Up to this point, our discussion has been based on the assumption that the evolution of a technology is a relatively continuous process without major discontinuities. Historically, this is sometimes not the case. Technological breakthroughs must be considered if only to place such events in context with the overall problem of technology tracking.

We define a "breakthrough" as being an unpredictable event in which very significant improvements are made on one or more critical performance parameters over a relatively short period of time. In the system under study here, the leading critical performance parameter is suggested to be a sharp impact in the direction of reducing end-product cost of liquid hydrogen, liquid oxygen, and any coproducts.

Thorough study of the relevant technologies can provide some indication of which ones have a greater chance of experiencing a breakthrough than others. However, we find no consistent or guaranteed utility in such an effort because of the intrinsic unpredictable nature of the "breakthrough process." No specific action to implement any special effort to attempt to predict or search for such events is recommended. However, if such events do occur, any substantial technology tracking efforts should provide for the earliest practicable detection of their occurrence.

#### Recommended Considerations in Technology Tracking

It is recommended that any technology tracking effort be carried out from two specific points of view:

1. Technologies should be tracked as "groups" encompassing the three primary areas of technology comprising the proposed non-fossil hydrogen production system as illustrated in Figure 9-4. Thus, technologies should be tracked in three groups: non-fossil energy conversion, hydrogen production, and liquefaction technologies. Energy form or finished product storage technology, where required, should be considered as a subset within each of these three principal technological areas.
2. As improvements in any or all of these principal technologies are detected, their impact should be assessed on the final product costs considering all subsystem design options as illustrated in Figure 9-5. As an example, the fact that a certain technological improvement may make a cogeneration application or a particular design option, not previously considered, practical to implement must not fail to be detected.

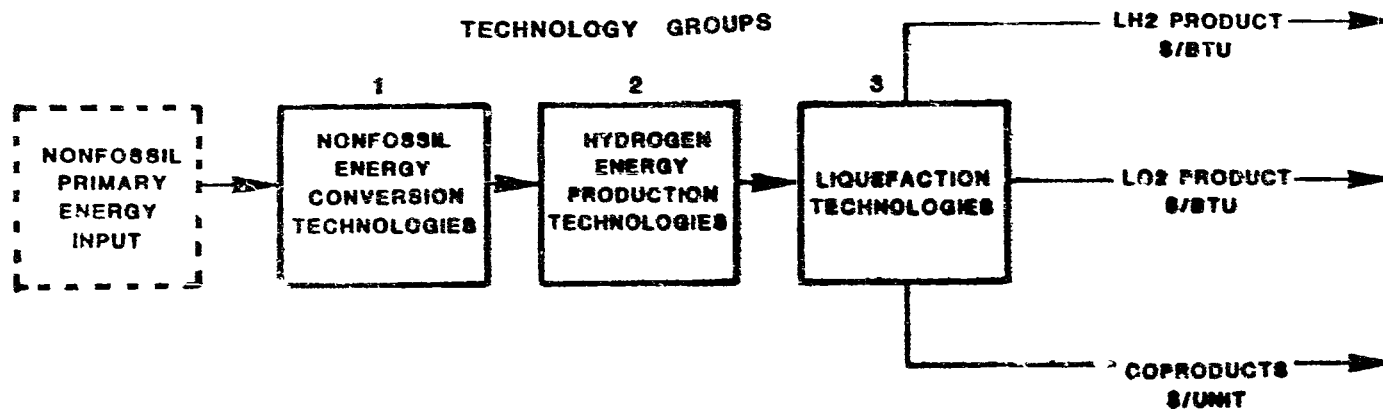


Figure 9-4. BASIC TECHNOLOGY GROUPS TO BE CONSIDERED IN TECHNOLOGY TRACKING

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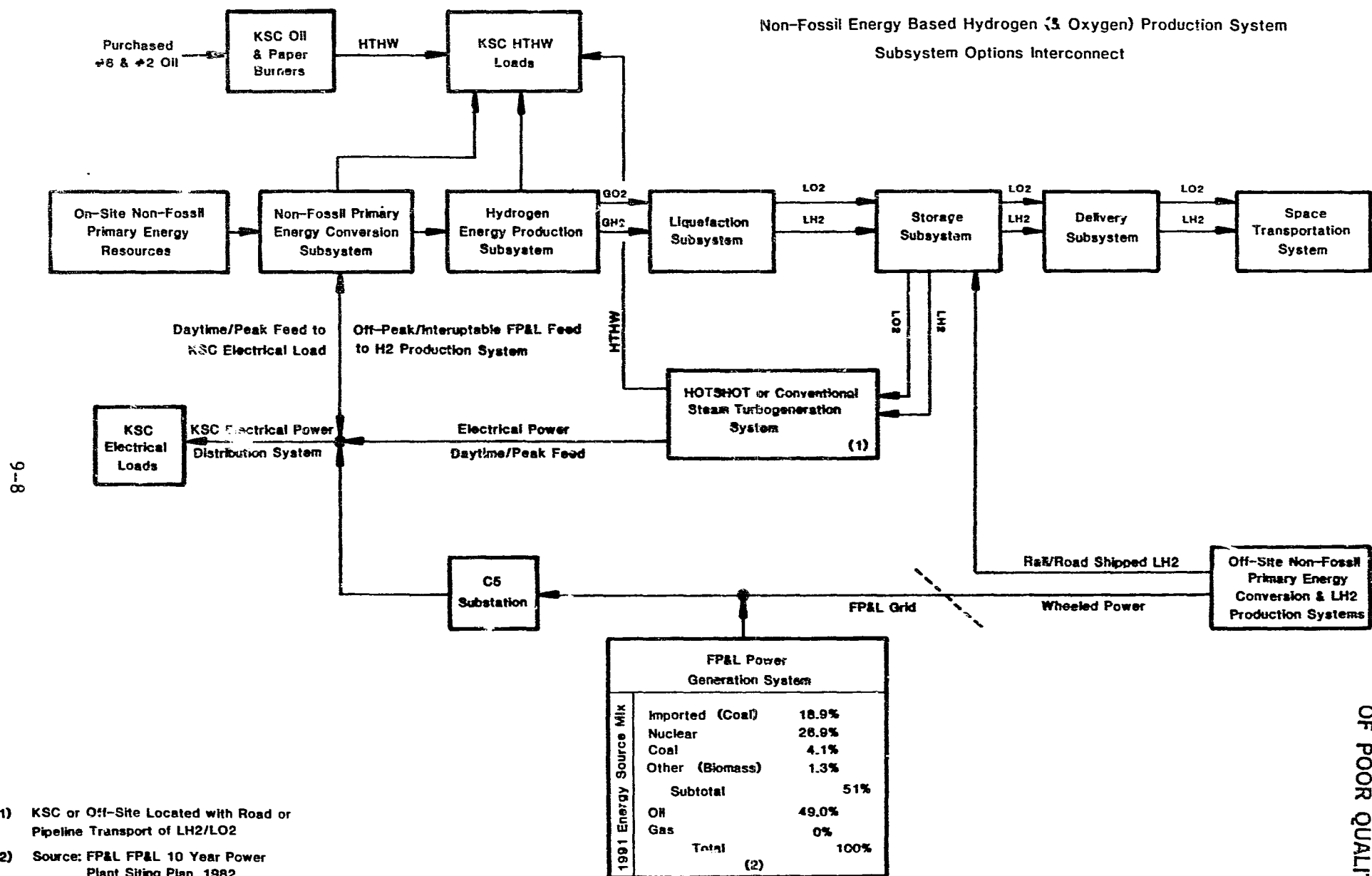


Figure 9-5. OVERVIEW OF NON-FOSSIL LIQUID HYDROGEN PRODUCTION SUBSYSTEMS AS INTERFACED WITH RELATED SUBSYSTEMS AND SYSTEMS

## Technological Options to be Tracked

Viewing the KSC-expressed period of interest broadly including post-2000 implementation, the time span of consideration is sufficiently broad, even considering the "by decades" historical development rates previously discussed, that no technological option should be deleted from the full list of options presented in Table 9-3 and those discussed elsewhere in the report.

## Information to be Gathered

In review, the basic reason for establishing and maintaining some organized approach to technology tracking is to maintain a focused, continuing awareness of the status of a broad range of applicable technologies in terms of meeting specific KSC requirements. The appropriateness in terms technology-readiness, is in the framework of systems capable of producing specific quantities of specific products at specific costs and on specific schedules. Until a technology evolves to a commercializable technology, it is most likely not a candidate for implementation at KSC.

As the range of technological options is broad, so also is the range of considerations in evaluating any candidate technology. A detailed listing of representative screening criteria is presented in Table 9-4. The developments in any area of technology may be impressive in a technological sense, but it must be constantly recalled that their true significance is in a systems applications setting. A technology simply cannot be considered as a real candidate unless the construction and operation of a liquid hydrogen production system using that technology can be undertaken with full confidence that schedules and budgets will be met.

## General Programmatic Approach Recommended

Two basic options of approach exist and either may be selected by KSC:

1. To provide adequate manpower resources to maintain a continuous technology-tracking activity for the purposes at hand, or
2. To implement a scheduled, periodic effort to survey such technological development, (e.g., annual update of a basic technology assessment document).

The basic resources required, methods of carrying out the technological assessments, etc., are broadly known but planning should be detailed if a technology-tracking effort is to be mounted (beyond the scope of the present study). It is roughly estimated that 1/4 man-year per year would be an appropriate level of effort for such a technology tracking activity. This level would only be required to be increased where some specific development, or a set of significant cumulative developments, appear to indicate that a more thorough systems analysis is required to assess impacts on potential system performance. Such events are not predictable but might generally be expected at 3-5 year intervals.

Table 9-3. SUMMARY OF CATEGORIES OF TECHNOLOGICAL OPTIONS FOR THE PRODUCTION  
OF LIQUID HYDROGEN FROM NON-FOSSIL PRIMARY ENERGY RESOURCES

Non-Fossil Primary Energy Resources for Evaluation

Solar Energy

Non-Concentrating

Concentrating

Nuclear Energy

Fission Burner Reactor

Fission Breeder Reactor

Fusion Systems

Geothermal Energy

Non-Fossil Primary Energy Conversion Technologies for Evaluation

Direct

Photic

Biophotolysis

Photocatalysis

Photoelectrocatalysis

Electric

Photovoltaic

Thermoelectric

Thermionic

Thermal

Thermal Engines

Direct Thermal Water Splitting

Thermochemical Water Splitting

Hybrid Electrolytic-Thermochemical Water Splitting

Indirect

Mechanical

Wind Energy Conversion Systems (WECS)

Ocean Thermal Energy Conversion Systems (OTEC)

Wave Systems

Hydropower

Biological

Hydrogen Energy Production Technologies for Evaluation

Electrical Generation

DC Machines

AC Machines

Homopolar Machines

Magnetohydrodynamic Machines

Electrolysis Systems

Unipolar Tank Electrolyzer

Bipolar Filter-Press Electrolyzer

Solid Polymer Electrolyzer

High-Temperature Electrolyzer

Hydrogen Liquefaction Technologies

Joule-Thomson Expander Technology

Magnetocaloric Refrigeration Technology

Table 9 4. 2nd LEVEL SCREENING CRITERIA LIST

Applicability of Technology

- Ability to quantify 1st level attributes of the technology
- Reliability or confidence in quantitative evaluation of 1st level attributes
- Effect of Time on 1st level attributes evaluation
  - Areas of improvement
  - Resources requirements for subject improvement
  - Probability improvement will be achieved
- Use of rare, costly, or strategic materials

Application of a technology to a system that meets all operational requirements over the system life cycle under site-specific conditions

Operational requirement: to deliver liquid hydrogen (and oxygen) of specified properties, in specified quantities, to a specified location at specified times at a contracted cost per unit product over a specified multi-year time period with a specified first delivery date.

- Design and specification for procurement under site-specific conditions
  - System, subsystem, assemblies, and components defined to support design detailing level
  - Reliable delivery dates available in appropriate quantities
  - Reliable pricing available in appropriate quantities
- Construction
  - Amenability to construction under site-specific conditions
    - Pre-planning capability
    - Scheduling controllability
    - Costs controllability
    - Reasonableness of instruction requirements
    - Organization controllability
    - Control and expediting controllability
    - Superviseability
    - Progress monitorability
    - Acceptance and turnover control
    - Maintenance and operation follow-up requirements
- Operation under site-specific conditions
  - Efficiency
    - Duty cycle
    - Under full load
    - Under part load
    - While load tracking
    - Age effects
  - Outage characteristics (EPRI-TAG definitions)
    - System
    - Subsystems
    - Assemblies
    - Critical components
  - Useful life with maintenance and repair
    - System preventive maintenance program (PMP) effectiveness
    - Subsystems PMP effectiveness
    - Assemblies PMP effectiveness
    - Critical components PMP effectiveness



Table 9-4, Continued

- Feedstock requirements
  - Description and specification
  - Amount required per unit of plant output
  - Storage, treatment, and feed requirements
- Waste products
  - Description and characteristics
  - Amount generated per unit of plant output
  - Storage, treatment, and disposition requirements
- Coproducts
  - Type and characteristics
  - Amount generated
  - Realistic economic value and disposition options
- Other operational considerations
  - Amenability to modularity and modularity effects expected
  - Minimum economic module size
  - Manufacturing learning and cost reduction potential
  - Construction learning and cost reduction potential
  - Preventive maintenance plan module definition
  - Ability to track KSC long-term load development
- Start-up requirements
  - Personnel related
  - Materials related
  - Equipment related
  - Other start-up unique operational requirements
- Ambient conditions compatibility
  - Environmental corrosion susceptibility
  - Weather conditions survival
  - Operating temperature limits
- Environmental impact
  - Site area requirements ranked with alternatives
  - Locating/siting options ranked with alternatives
  - Site options economic comparisons
  - Environmental evaluation of candidate non-fossil hydrogen production systems solid, liquid, and gaseous wastes, feedwater requirements and presence of hazardous compounds
- Environmental consequences
  - Manmade resources:
    - Land use
    - Recreation and scenic resources
    - Cultural resources
    - Socioeconomic impact
  - Natural Resources:
    - Air quality
    - Surface water (availability and impacts on quality)
    - Ground water
    - Aquatic ecology and fisheries
    - Upland vegetation and wildlife
    - Threatened and endangered species
    - Wetlands and wetlands wildlife
    - Floodplains
    - Geology and soils
    - Environmental noise
    - Radiological impacts
    - Solid, liquid, and gaseous waste disposal

Table 9-4, Continued

- Operating economics characteristics per EPRI-TAG Methodology
  - Cost analysis boundary definition
  - General attributes
  - Under government ownership (cost/million Btu of delivered product)
  - Under utility ownership (cost/million Btu of delivered product)
  - Under public ownership under renewable energy technologies incentives, advantages, and limitations (cost/million Btu of delivered product)

General Considerations

- Security of product supply to KSC for the system life-cycle
- Overall ability to meet shuttle program requirements
- Contribution to KSC mission objectives
- Contribution to NASA mission objectives

Specific Examples of Technology Tracking Significant Future Milestones

For the projected KSC non-fossil liquid hydrogen production system's long-term interest, future progress in the related technologies and systems areas is thus to be appropriately tracked. Again, the three "technology groups" of Figure 9-4 is a helpful categorical breakout and will be adapted here. To close out this discussion, a number of pertinent examples of "future milestones" will be presented to provide a further technical focus.

The logic of approach here is to seek developmental "thresholds of progress" in the non-fossil liquid hydrogen technological arena indicative of major readiness status, including "quasi-breakthroughs" when and if these occur. Once such milestones are reached, it will be pertinent to re-estimate ultimate liquid hydrogen-plus-coproduct costs. As usual, these must then be compared with the alternatives as input for decision-making, e.g., with regard to then developing the non-fossil-based capability, or not.

In relating the following examples, it is noted that, first, emphasis remains on the 1987-2000 time-period which suggests that those technologies at the concept-level, or just entering basic research, will--in general--not be in the running. Nevertheless, emphatically, this class of technologies should be studiously monitored. Breakthroughs are always possible.

Secondly, the considerations here lean heavily toward a KSC-siting approach with certain obvious exceptions, e.g., OTEC. This means that such possibilities which have been suggested, such as importing Canadian-produced liquid hydrogen (from low-cost nuclear or hydropower) are not considered. This does not mean that such alternatives are to be discounted; they may indeed make sense.

Finally, the items below are only illustrations and examples. Many other possibilities remain to be identified and characterized using an updating methodology. Such is considered beyond the scope of this study. For convenience, these examples are assembled in tabular form (Table 9-5).

Table 9-5. EXAMPLES OF TECHNOLOGY-TRACKING FUTURE MILESTONES

<u>Technology Areas</u>	<u>Suggested Key Progress Thresholds</u>
(Group 1: Non-Fossil Energy Conversion Technologies)	
Photovoltaic Modules	50 MWp/yr U.S. production, \$2.50/Wp (installed) price
Solar Thermal Central Receiver Systems (Power Tower)	3 installations @ 50+ MWe
Ocean Thermal Energy Conversion (OTEC) Systems	5 "commercial facilities" operating worldwide
High Temperature Gas-Cooled Reactor Modules	3 installations @ ca. 25 MWe operating capacity
Solar Ponds	5 MWe-sized installations fully operational; KSC-site peculiar problems solved (e.g., "rain cover")
Wind Energy Conversion Systems (WECS)	3 offshore WECS "commercial facilities;" or commercialization of cost-competitive "ultra-low wind speed (3-5 mph cut-in, 8 mph average speed)" systems
Biological Conversion	Several "multi-acre" installations operating stably over many months under conditions practical at KSC (e.g., feed-stocks, waste-stream removal)
(Group 2: Hydrogen Energy Production Technologies)	
High-Temperature Water Electrolyzers	Demonstrated economic MWe-sized units operating at cell voltages of 1.1-1.2 v and life-proven materials makeup
Thermochemical or Hybrid Water-Splitting Systems	Pilot-plant scale demonstration reflecting marked cost/efficiency gains over equivalent-technology electrolyzers
Direct Thermal Water-Splitting Systems	(Same as above)
Photolysis, Photocatalysis, Photoelectrocatalysis, et al., Water-Splitting-Based Systems	Cost-effective (materials, efficiency, etc.) bench-scale full systems operation assuming multi-year, stable operation
(Group 3: Hydrogen Liquefaction Technologies)	
Magnetocaloric Refrigeration-Based Liquefier Systems	Commercialized hydrogen-liquefier units on the market in the fractional-ton/day range or larger

References Cited in Section 9

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- 9-2. Fisher, J.C. and Pry, R.H., "A Simple Substitution Model of Technological Change," General Electric Company, Schenectady, NY, Report No. 70-C-215, June 1970.
- 9-3. Battelle-Columbus Laboratories, "Interactions of Science and Technology in the Innovative Process," prepared for the National Science Foundation under Contract NSF-6667, 1973.

## 10. KEY OBSERVATIONS, CONCLUSIONS, AND RECOMMENDATIONS

### Key Observations

In review and summary of the material presented in this report, a number of salient findings stand out of key importance:

1. For the 1990-2010 time-frame, non-fossil-derived liquid hydrogen (and liquid oxygen) systems, represented here by the "finalist" solar photovoltaic (PV)-based and power tower (PT)-based systems, are found to be potentially cost competitive with projected conventional industrial sources based on fossil energy and feedstock, e.g., natural gas steam reforming.
2. For the assumed range of capital costs, the PV- and PT-based liquid hydrogen production system approaches were observed to yield roughly equivalent product costs.
3. Not given "finalist" status examination in this assessment, two other candidate non-fossil liquid hydrogen production approaches appear to yield potentially equivalent-range product costs: OTEC- and modular nuclear fission (HTGR)-based systems. Neither can be counted on, however, to be available at assumed costs within the 1987-1992 IOC window.
4. Other than the modular-HTGR system, which could conceivably be sited at KSC, no other nuclear-based known options (fission or fusion) qualify as candidates during this century.
5. Geothermal energy-based systems of those types under active investigation are not promising because of Florida's low-resource and limiting geophysical characteristics.
6. Solar-based indirect-conversion approaches, which may be well-proven or are promising technologies at certain other sites, are clearly decisively input-resource limited for KSC siting: hydropower, wind-energy, OTEC, wave-energy.
7. Advanced, in-research stage solar hydrogen production concepts, often involving direct water-splitting reactions, even if ultimately successfully developed, cannot be counted on with any reasonable confidence level until after 2000.
8. Through 2000, systems to meet the KSC liquid hydrogen production goals will most probably be based on (1) conventional water electrolysis, and (2) conventional liquefaction technologies and systems.
9. With oxygen, as well as hydrogen, being inherently available at the stoichiometric ratio (8:1 by mass) from the water electrolysis process (as with any direct water-splitting process), and with its liquefaction being readily accommodated in a slightly modified, otherwise conventional hydrogen liquefier, the provision of liquid oxygen coproduct adequate for KSC's overall needs is economically practical.
10. Returning to the nominally selected "finalist" systems (PV-, PT-based), it should be emphasized that attaining competitive product cost status

depends fundamentally on achieving significantly lower PV-module and heliostat capital costs than those quoted presently by manufacturers. Additionally, further detailed assessment of PT-solar subsystem performance in the KSC non-desert insolation environment is critically needed (the study made significantly optimistic assumptions here).

11. Although considerable liaison was carried out with the electric utility serving KSC (Florida Power & Light Company) in the course of the study, the issue of utility interfacing with a KSC-sited direct solar energy-based system remains cloudy, and should be further explored in view of possible synergistic interactions.
12. For a set of assumed (but not FPL derived) electricity costs of \$.03 and \$.06/kWhr (average, around-the-clock), direct powering of a KSC-sited electrolyzer/liquefier resulted in quite competitive product costs, as low as one-half conventional-source liquid hydrogen. Additionally, utility-augmented solar-based operation was shown to offer significant product cost benefits.

### Conclusions

From these key observations and other findings presented herein, a number of first-order conclusions can be tentatively supported:

1. Non-fossil liquid hydrogen production meeting KSC requirements as a basic approach, is technically feasible based on current state-of-the-art developments. Further, exemplary candidate systems (e.g., solar-operated) are compatible with KSC-siting from a resource-availability, land-use, and environmental impact standpoint.
2. Based primarily on achieving "optimistic but achievable" solar-related equipment capital costs (e.g., PV modules, heliostats), and assuming nominal (e.g., 3%) cost-escalations (above inflation rates) for the present conventional and energy-intensive fossil-based product-supply means, the leading non-fossil production candidates are also potentially cost-competitive in the 1990-2010 period.
3. For the 1987-1992 initial operating capability (IOC) "window" constraint, along with the KSC-site characteristics taken generally, the leading candidate non-fossil technical approaches are solar-direct in nature, specifically those based on photovoltaic and concentrating solar-thermal energy conversion (the latter represented by the power tower approach).
4. Potentially meeting a 1992-2000 IOC, given considerably accelerated development over that perceived otherwise to occur, one solar-indirect-based and one nuclear-based candidate comes in view: (1) OTEC with remote siting and (2) modular-HTGR on, or near, KSC.
5. Through a 2000 IOC, it is highly predictable that the non-fossil operated sequential water-splitting and product liquefaction steps will be based on "conventional, improved" technologies and systems, namely, water electrolysis and thermomechanical-refrigeration liquefaction processes.

## Recommendations

It logically follows from the findings developed in this study that, if KSC-interest in the non-fossil liquid hydrogen production alternative is to be followed-up, certain priority actions can be recommended:

1. The PV- and PT-based leading candidates should now be further evaluated with the following emphasis:
  - PV: hands-on experience at KSC, including detail engineering design and implementation of a "representative modular system" based on state-of-the-art equipment, and specifically examine "intrinsic matching" vs. incorporating maximum-power tracking
  - PT: critical evaluation of solar-conversion equipment in the specific KSC insolation and operating environments including certain interesting variants on the heat-to-electricity step (e.g., acyclic d.c. generator).
2. A formal technology-tracking activity should be supported by/at KSC (along the lines outlined in Section 9).
3. KSC should support, on a continuing basis, systems engineering treatment and documentation of leading non-fossil liquid hydrogen production system approaches, the "finalist" systems of Section 8 and others as appropriate, this should be developed beyond the present-study scope and then maintained at roughly equivalent level-of-depth as for any fossil-based options, to permit meaningful comparisons and reliable input for decision-making.
4. Based on definite positive indications, but not confirmed within the present study, KSC should consider establishing active liaison and cooperative studies with Florida Power & Light Company to address electric utility/non-fossil production system interfacing potential payoffs to both parties.

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APPENDIX A

Solar-Driven Liquid Metal MHD Generators for  
Hydrogen Production

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# SOLAR-DRIVEN LIQUID METAL MHD GENERATORS FOR HYDROGEN PRODUCTION BY WATER ELECTROLYSIS

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## ABSTRACT

Solar-driven liquid-metal MHD generators are reviewed as a possible non-fossil power source for a large-scale hydrogen-production facility. The LMMHD technology base warrants a feasibility of such application but the employment of a high-efficiency system for near-term hydrogen production is premature. However, for the significant advantages in the efficiency and cost of the system, it is recommended to develop the solar LMMHD cycle as the topping cycle to be retrofitted to a solar steam power generator which meets the near-term requirements.

## INTRODUCTION

Large-scale production of liquid hydrogen (LH<sub>2</sub>) and liquid oxygen (LO<sub>2</sub>) is required for supporting frequent launches of the Space Shuttle in the near future. For long-term supplies, it is desirable to produce the LH<sub>2</sub> and LO<sub>2</sub> by non-fossil, renewable energy sources.

The solar-driven liquid-metal MHD generator is one of possible approaches identified earlier by E:F studies for NASA-Kennedy Space Center planners (Reference A-1). In this review, which is part of the E:F studies, first the historical background and the basic arrangement of the LMMHD system are outlined, then the status of the LMMHD technology on its components and system is evaluated. Advantages of the solar LMMHD system for hydrogen production are pointed out and the review is concluded with recommendations.

## LIQUID METAL MHD GENERATORS

A liquid metal MHD generator was originally proposed by D. Elliott (Jet Propulsion Laboratory) as part of a space power system using a nuclear reactor. Two metals--cesium and lithium--were considered as the working fluids of the generator. The cesium (Cs) leaving the radiator as a condensate is pumped through the regenerative heat exchanger to the nozzle where it vaporizes as it comes in contact with the liquid metal lithium (Li) from the liquid loop. The Cs accelerates the Li in the nozzle, thus imparting an increased kinetic energy to the separator and then passes back to the radiator. The Li leaves the separator at a relatively high velocity ( $\approx 150$  m/s) and flows through the MHD generator. The cooled Li is reheated in the heat source and pumped back to the nozzle.

The disadvantages of Elliott's cycle (i.e., a fixed and high operating temperature range,  $> 1700$  K, and the difficulty in handling the liquid flow in the MHD channel) were alleviated later by the adoption of a two-phase mixture at Argonne National Laboratory. The basic idea was to utilize the fact that a two-phase mixture is a compressible fluid and thus is an effective thermodynamic working fluid that could be expanded directly through the MHD generator like a gas expanding through a turbine from which electric power is extracted. The mixture, as it leaves the generator, is further

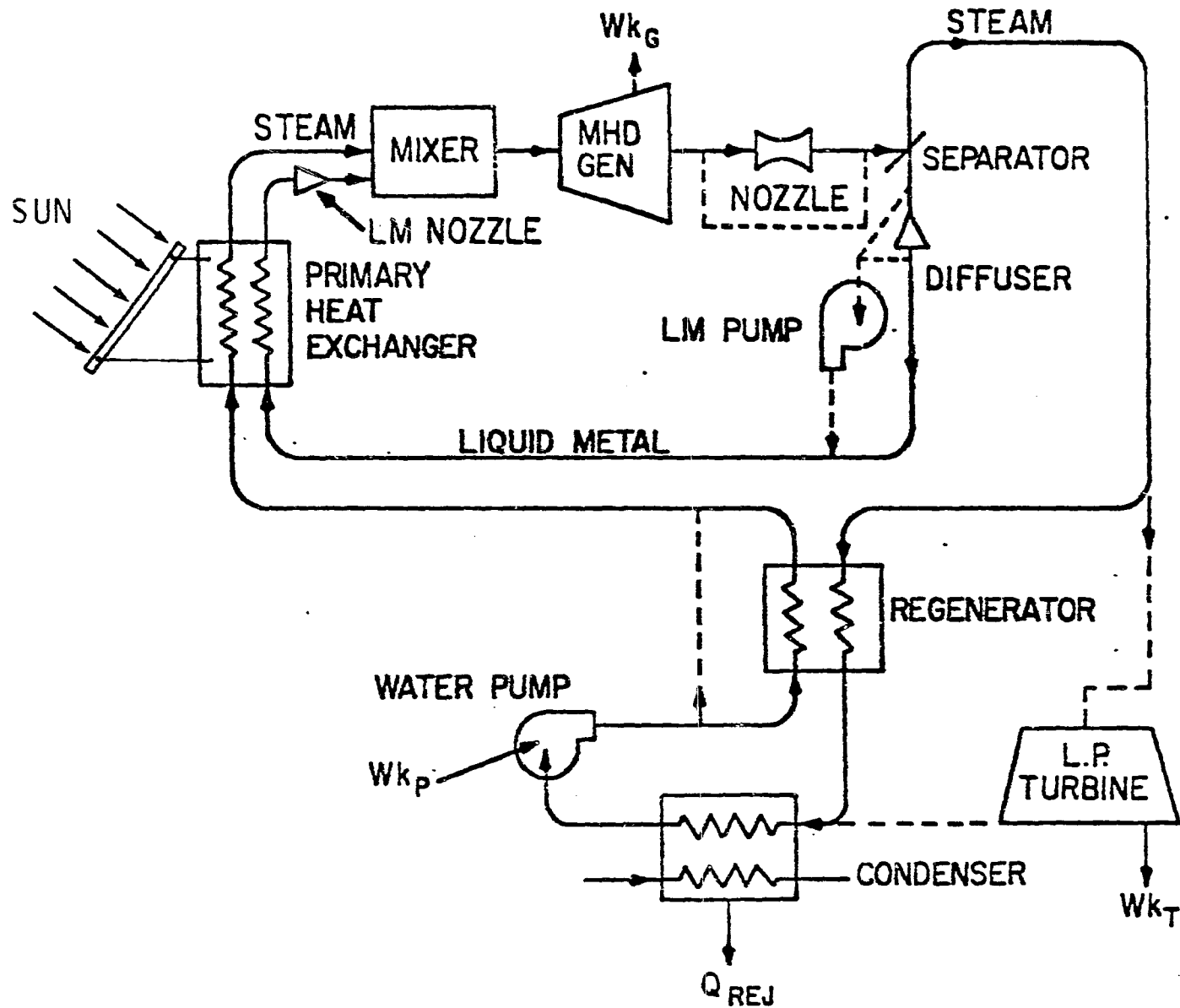
expanded in a nozzle to increase its kinetic energy and is then sent to a separator. There, the liquid metal is separated from the gas and is returned via a diffuser through the heat source to the mixer. The gaseous working fluid is then handled as in a normal Brayton cycle. It is passed through the regenerative heat exchanger to the heat sink and is then compressed and sent back to the mixer via the heat source. The gaseous component is the thermodynamic working fluid, and the liquid metal (which remains in a closed loop) is the electrodynamic working fluid. At ANL, a Na-K<sub>2</sub> LMMHD generator has been tested and an efficiency of greater than 50% at 1500 K was estimated.

The heat sources considered by ANL researchers were fossil combustion, high-temperature gas-cooled nuclear reactors (HTGCR), fusion reactors, and liquid metal fast breeder reactors. Recently, utilization of the solar radiation as the heat source of LMMHD for space power production has been proposed. Also, the terrestrial applications of the solar LMMHD have been studied by the ANL group.

The liquid metal MHD (LMMHD) power systems can be classified in two types, namely, Rankine cycle and Brayton cycle systems, depending on the choice of thermodynamic fluid. Figure A-1 is one kind of Rankine cycle LMMHD system in which an organic liquid with low-temperature boiling point is used as a thermodynamic fluid. This system is suitable for heat/electricity cogeneration at a temperature < 1000 K, but the electrical efficiency is limited to 10% (Reference A-2). Therefore, this type of LMMHD system is ruled out a priori as an efficient solar electric power source for electrolytic hydrogen production process which should render near-term application. The following discussion is, therefore, limited to the Brayton cycle LMMHD systems.

Figure A-2 shows a Brayton cycle LMMHD system in which the liquid metal is heated by a solar collector via a heat exchanger. As analyzed by Pierson, et al. (Reference A-2), this system could be operated at a temperature up to 1500 K and, consequently, a high system efficiency (up to 50%) is projected. Table A-1 lists the component performance parameters of the Brayton cycle adopted in his analysis. Among other alkaline metals, sodium was chosen for the working liquid metal which has good heat transfer properties and low vapor pressure at high temperature (up to 1000 K) which are important requirements of the efficient LMMHD cycle. However, the temperature above 900 K Li should be used as the working metal. This is due to the efficiency reduction by the excessive vapor pressure of the liquid metal which is carried over with the gas from the separator. The mixer temperature limit of Li is 1300 K. The mixer exit pressure is kept 50.07 MPa (735 psia). The cycle employs a primary heat exchanger to couple the collector supplied solar energy with the liquid metal. The gas (helium) is heated by the liquid in the mixer. Although this cycle may be adapted to many different heat sources such as coal, oil, geothermal, etc., a more simplified and efficient cycle could be developed with the solar energy by eliminating the primary heat exchangers and utilizing a focusing optics for coupling the solar energy directly with the working fluids.

Figure A-3 is a schematic of the direct-heating solar LMMHD system (Reference A-3). The system consists of (a) a large solar collector, (b) an oven heated by solar energy, (c) a mixer for mixing the gas and liquid metal, (d) a MHD generator including a magnet, inverters, and a power transmission



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Figure A-1. SOLAR RANKINE LMHD CYCLE (Reference A-2)

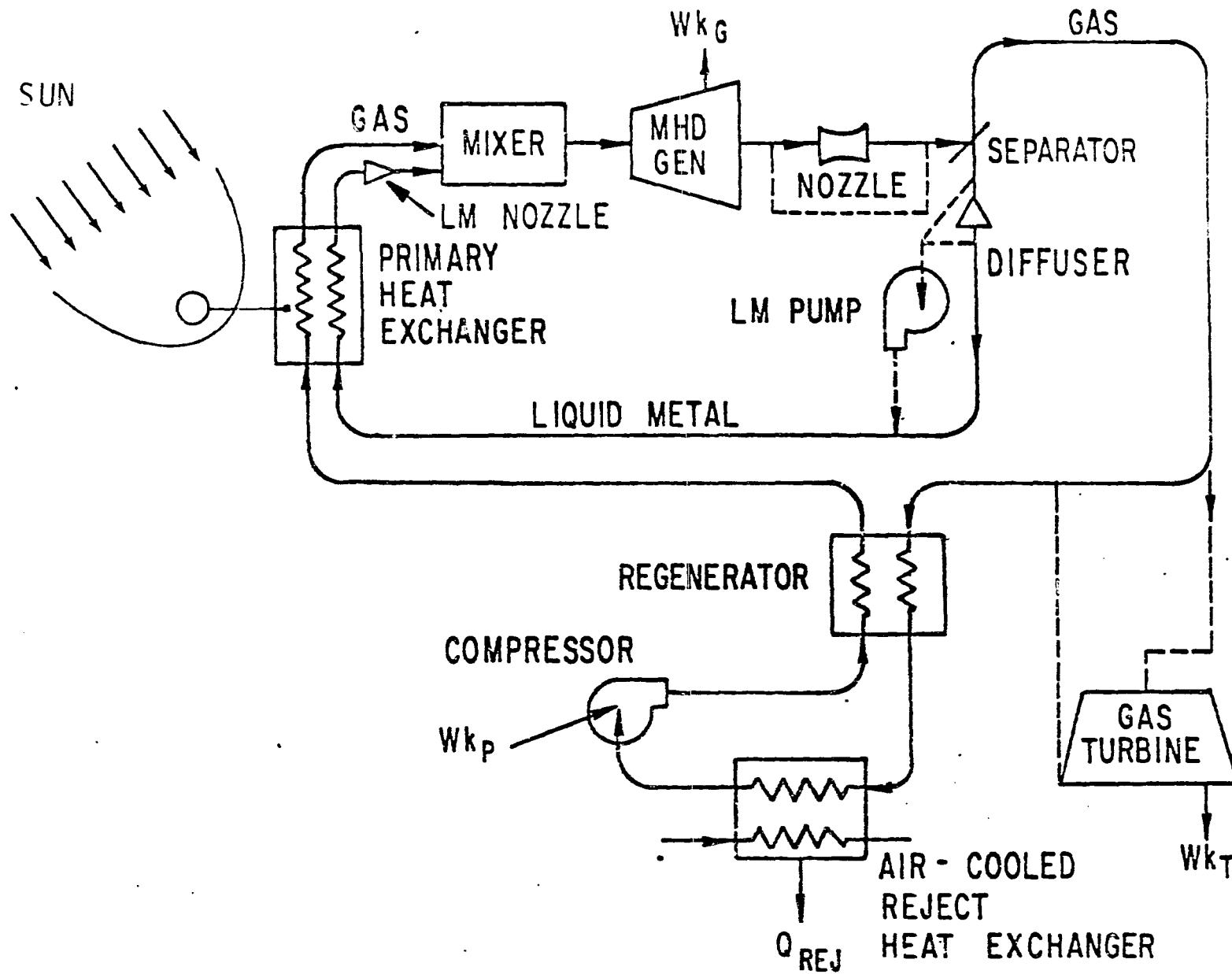


Figure A-2. SOLAR BRAYTON LMMHD CYCLE (Reference A-2)  
See also Figure A-4 for the System Efficiency

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Table A-4. COMPONENT PERFORMANCE PARAMETERS, LMMHD BRAYTON CYCLE  
(Source: Reference A-2)

PRESSURE DROP:

$\Delta p_{\text{mixer}} = 34.5 \text{ kPa (5 psi)}$   
 $\Delta p_{\text{primhx}} = 68.9 \text{ kPa (10 psi)}$   
 $\Delta p_{\text{sep}} = 0 \quad \Delta p_{\text{rejhx}} = 0.025 \text{ } p_{\text{reg hot}}$   
 $\Delta p_{\text{reg hot}} = 0.015 \quad p_{\text{turb}} \Delta p_{\text{reg cold}} = 0.015 \text{ } p_{\text{rejhx}}$

EFFICIENCIES:

Compressor	0.88	Diffuser	0.9
Turbine	0.9	Liq. Metal Pump	0.85
Nozzle	0.9	LMMHD Gen.	0.8

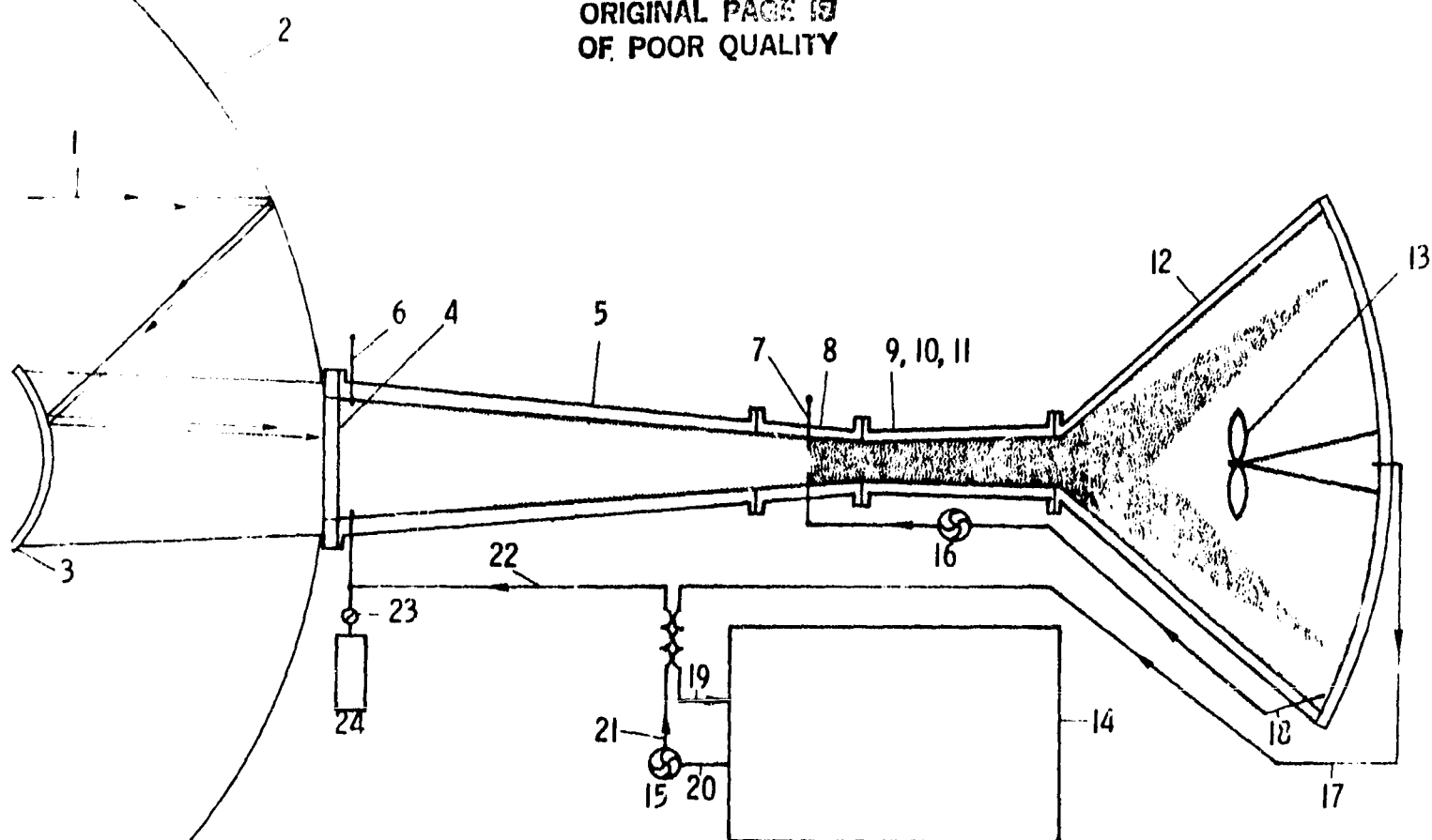
HEAT REJECTION CONDITIONS:

Ambient Temperature: 297.2 K (75°F)  
 Pinch Point: 11.1 K (20°F)

OTHER:

Three Compressor Stages With Intercooling  
 Regenerator Effectiveness: 0.9  
 Separator Loss: 10% of kinetic energy at inlet.

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- |   |                       |
|---|-----------------------|
| 1. solar radiation                                      | 2. solar collector    |
| 3. directing mirror                                     | 4. oven window        |
| 5. solar oven   | 6. working gas inlet  |
| 7. liquid metal inlet                                   | 8. mixer              |
| 9,10,11 MHD generator with magnet and power conditioner |                       |
| 12. diffuser  |                       |
| 13. separator   | 14. radiator          |
| 15. compressor  | 16. liquid metal pump |
| 17. gas loop  | 18. liquid metal loop |
| 19. hot gas inlet                                       | 20. gas outlet        |
| 21,22 cold gas line                                     |                       |
| 23. valve   | 24. gas reservoir     |

Figure A-3. DIRECT-HEATING SOLAR LMMHD CYCLE

circuit, (e) a gas/liquid metal separator, (f) a pump for recycling the liquid metal and a compressor for the working gas, and (g) a cooling unit for the gas. The advantages of direct-heating solar-driven LMMHD are:

- The solar collector could be constructed with very light material of high reflectance to focus solar radiation at very high concentrations similar to solar furnace systems.
- No primary heat exchanger is required since the mixture itself functions also as a solar absorber thus improving the system efficiency and saving the cost.

#### STATUS OF LMMHD TECHNOLOGY

Since 1961, the LMMHD development has 20 years of history, and numerous institutions worldwide have participated in hope to couple the cycle with various heat sources. Some of these institutions are:

1. Jet Propulsion Laboratory: Ce-Li flow with up to 150 m/s speed and temperature up to 1250 K has been studied for a LMMHD channel (Reference A-4).
2. Argonne National Laboratory: the LMMHD component development was pursued and the most active experimental and theoretical analysis center until recently (Reference A-5).
3. Ben-Gurion University of the Negev: since 1975, applications of LMMHD to solar collectors and other low temperature heat sources have been studied. A low temperature ( $<500^{\circ}\text{C}$ ), 10-kW LMMHD system with organic vapor is in the prototype engineering stage (Reference A-6).
4. Massachusetts Institute of Technology: LMMHD generators and pumps were studied earlier than 1961 and later its space application with a high-temperature system was investigated (Reference A-7).
5. Atomics International: LMMHD induction generators were studied in the 1970's (Reference A-8).
6. Cie Electro-Mecanique, France: an "emulsion LMMHD" concept was developed. Recently, solar LMMHD systems have been studied (Reference A-9).
7. Technische Universitat Berlin, Germany: a large MHD program was carried out in the 1960's and 1970's (Reference A-10).
8. Brookhaven National Laboratory: repetitive liquid metal slug MHD studied (Reference A-11).
9. NASA-Langley Research Center: direct solar-driven LMMHD generator is proposed recently and a solar-oven experiment has been planned (Reference A-3).

Although most of the above institutes have now phased out the LMMHD program from their main-line efforts, the technology base required to build a practical LMMHD power system can be extracted from their contributions. The status of development of the major components in the LMMHD system, i.e., the mixer, generator, two-phase nozzle, separator, diffuser, and solar collector, are briefly reviewed below.

## Generator

The two-phase LMMHD generator is the key component in the cycle. Therefore, attendant loss mechanisms have been extensively studied. These are end, viscous, and shunt electrical, slip losses. The Ben-Gurion University program has focused on reducing these losses experimentally while analytical efforts have been made at Argonne National Laboratory where three types of computer models have been developed. The results of the experiments and the analyses show that the generator efficiency goal of 0.8 can be met with even small generators and easily attained with larger generators. One crucial test that remains to be done is that liquid-metal foams can indeed be generated with the acceptable void fraction of 0.7. Utilization of surfactants has been helpful for increasing the void fraction at ANL.

## Separator

High-performance gas-liquid separators have been developed for many industrial applications. Surface separators, rotating separators, and flat-plate separators have been tested. Rotating separators have shown that a gas-free liquid layer can be established and maintained and that kinetic energy ratios of in- and out-flows of near 0.9 are attainable.

## Mixers, Nozzles, and Diffusers

These components have been extensively tested at ANL, BGUN, JPL, and Technical University Berlin. Excellent agreements between experimental and theoretical results have been obtained and design requirements can be met easily.

## Solar Collectors

For solar LMMHD systems, a solar collector field with a central receiving tower such as SOLAR 100 is most suitable. Such collectors provide near 1000 K temperature to the absorber at the receiving tower thus adaptable to high temperature Brayton LMMHD generators. Since these facilities are well developed and the technology is already applied commercially, it is not reviewed here.

In summary, it is recognized that liquid metal MHD generators appear attractive when coupled to solar collectors, and technologies on the overall system and its components are readily available. However, there is no operational experience of high-temperature cycles which demonstrated high-efficiency power generation by a total LMMHD system to date. Therefore, near-term application of solar LMMHD cycles for large-scale hydrogen production is not recommended.

## ADVANTAGES OF A SOLAR LMMHD GENERATOR FOR WATER ELECTROLYSIS

Several advantages of using solar-LMMHD for hydrogen production via water electrolysis are recognized as follows:

1. Solar LMMHD generators produce high DC power at low voltages. An inverter is necessary to feed a conventional AC utility. However, water electrolyzer requires DC power at low voltage (<1000 V) and the LMMHD power output could be coupled directly with the electrolyzer. When the elec-



trolyzer is located nearby, little "ohmic loss" will tax on power distribution. If an AC-powered hydrogen liquefier which will consume approximately one-third of total power generated is used, an inverter may still be required.

2. Solar LMMHD generator is an ideal topping cycle for retrofitting solar steam powerplants for efficiency promotion. For near-term application of solar energy to hydrogen production, a steam powerplant placed on the central receiving tower of a solar collector field (such as SOLAR 100) may be advisable. After the LMMHD technology is matured, a LMMHD generator could be adapted as a topping cycle for the plant. An open-cycle LMMHD system has been considered for retrofitting coal-fired steam power plants which shows that over 40% increase in the plant efficiency could be realized by topping. There is no detailed study on the solar power system, but a parallel result is expected since the principle involved is identical, that is, the LMMHD cycle has a very small temperature difference ( $\sim 10$  K) between the entrance and exit two-phase flows, thus alters little the efficiency of the bottoming heat engine.
3. Unlike other heat sources, the solar energy is high-grade and clean. Therefore, the selection of gas and liquid metal for the MHD system is free from other considerations, such as chemical contaminations by the heat sources (coal, oil, etc.). Also, the operating temperature range can be predetermined easily by the solar collector geometry and the absorber to be used.
4. The economic advantage of the solar-driven LMMHD compared with a solar photovoltaics power generator is seen by the following examples. For electric power generation alone, the capital cost for the LMMHD system is estimated at \$88,000,000 for a 100-MWp plant consisting of four 25-MWp units (Table A-2), while the photovoltaic generator would cost over \$100,000,000 as estimated by Spratke, et al. (Reference A-12). This difference will reflect to the estimates of solar electric net costs (\$/kWh) in favor of the LMMHD system.

#### CONCLUSIONS AND RECOMMENDATIONS

The concept of a solar-driven liquid-metal MHD power generator for hydrogen production by water electrolysis is reviewed. The technology base soundly laid by the past 20 years of LMMHD research pursued worldwide has shown a feasibility of successful operation of the solar-driven system. However, there is no operational experience with system integration for a high-efficiency LMMHD system, thus excluding an early adaptation of the system to fulfill the near-term hydrogen production requirements.

It is recommended, in view of its projected advantages in the system efficiency and cost, that the solar-driven LMMHD system should be adapted and developed as a topping cycle to the solar steam powerplant which is immediately employable for the near-term requirements.

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Table A-2. 25-kW LMMHD CAPITAL COSTS (\$ THOUSAND), EXISTING TECHNOLOGY,  
NO COGENERATION (Source: E.S. Pierson, et al., January 1981, unpublished)

Equipment	Unit Cost	Units	Sub Total	Installation Factor	Total
Mixer	16	4	64	1.3	83
LMMHD Generator	30	4	120	1.3	156
Magnet	225	1	225	1.3	292
Nozzle	11	4	44	1.3	57
Separator/Diffuser	37	4	148	1.3	192
Power Conversion Equipment	1,090	1 set	1,090	1.3	1,417
Bus Bars	190	1 set	190	1.3	247
Compressor w/Drive	1,650	1 set	1,650	1.3	2,145
Piping	6	1 set	6	1.3	8
Reject Heat Exchanger	195	1	195	1.3	254
Regenerator	1,020	1	1,020	1.3	<u>1,316</u>
Subtotal:					6,177
Instrumentation & Controls (10% of Subtotal):					618
Miscellaneous Items (10% of Subtotal):					<u>618</u>
LMMHD TOTAL:					7,413
Collectors	\$270/m <sup>2</sup>	41667 m <sup>2</sup>	11,250	1.0	11,250
Tower	810	1	810	1.3	1,053
Receiver	1,800	1	1,800	1.3	<u>7,340</u>
POWER TOWER TOTAL:					14,643
TOTAL COST:					<u><u>22,056</u></u>

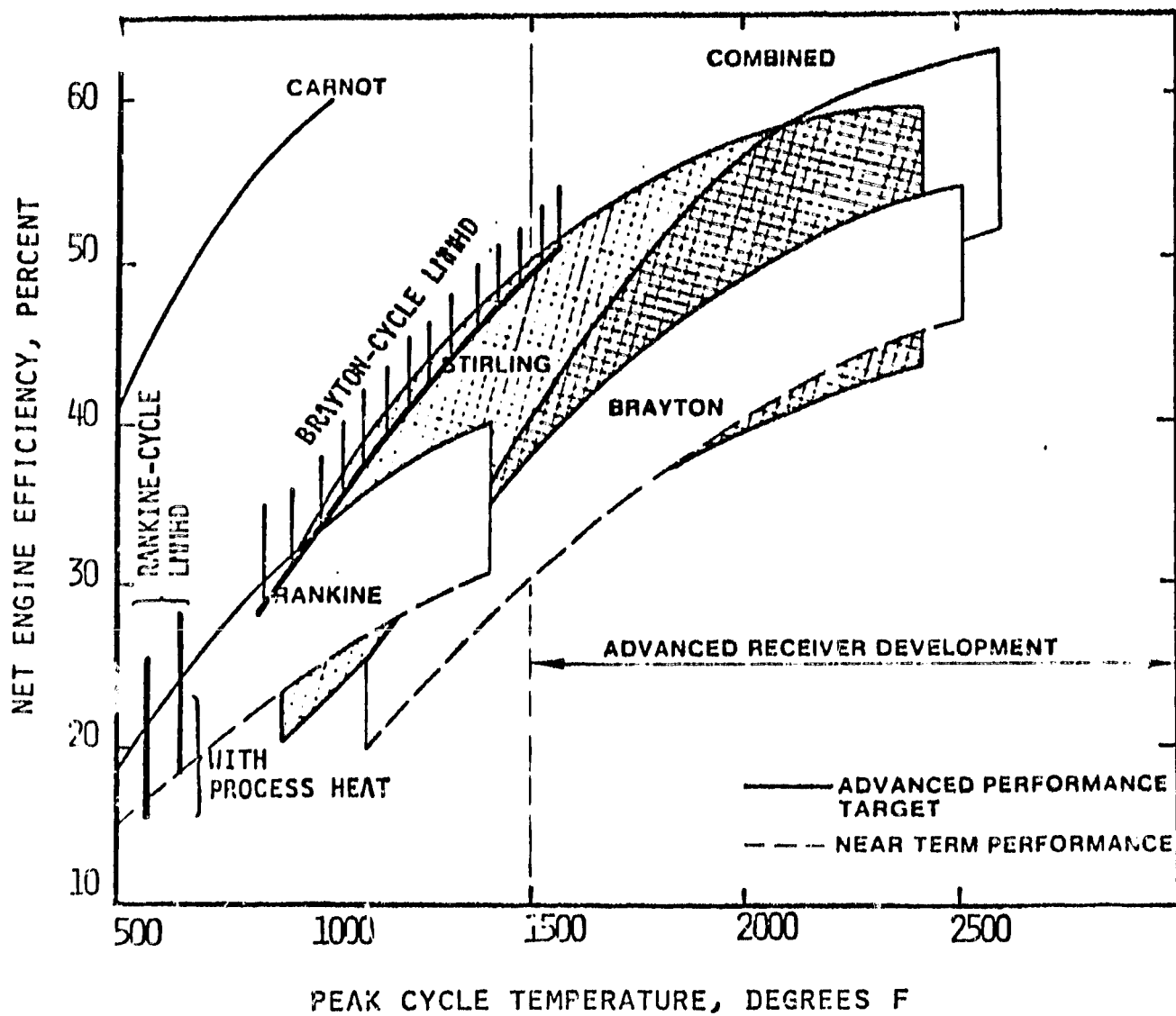


Figure A-4. PERFORMANCE COMPARISON: LMMHD AND OTHERS

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APPENDIX B-1

Magnetocaloric Liquefaction of Hydrogen

Dr. John A. Barclay  
Los Alamos National Laboratory

## LOS ALAMOS MAGNETIC REFRIGERATION PROJECT

### Overview

Our overall objective is to develop a more efficient, more reliable, less massive, and smaller refrigerator that is cheaper than existing gas-cycle refrigerators. Our major applications for such new refrigeration are liquefaction of cryogenics such as hydrogen and LNG, air separation for oxygen production, liquid helium for superconducting accelerators and generators, and spacecraft refrigerators for a variety of scientific and defense missions.

We are approaching this project from 4 K upward because the data-base is more established in the 4-20 K regime than in higher temperature regimes excluding room temperature. Our program has a research component designed to produce the data-base for refrigerators from 20 K to 300 K or higher. This includes basic work on magnetic materials, heat transfer, fluid dynamics, and pumps. The other major component of our program is the development of experimental prototypes that will test and, hopefully, prove that magnetic refrigerators can satisfy the high expectations that calculations on these systems promise.

The present status is that the basic research work is progressing well with major emphasis on the 20-77 K region at present. An excellent refrigerant,  $\text{GdNi}$  ( $T_0=68\text{K}$ ), has been fully characterized and initial results on general other materials indicate that there should be plenty of magnetic materials. Cost of the raw material, Gd, has been investigated and found to be reasonable (supplies are plentiful although not fully developed). The heat transfer and fluid dynamic work is well underway with indications that several possible geometries will provide the necessary high heat transfer. New ideas for low-temperature pumps indicate that greater than 65% overall efficiency is possible (with high reliability and long lifetime). Work is proceeding with several designs.

The development effort is focused on the 4-20 K, 1-W, wheel-type refrigerator that is undergoing initial testing at present. Several improvements have already been made on the magnet and dewar system for this refrigerator and prospects look excellent for this device. We are also in the process of designing a 20-77 K refrigerator to perform as a 10 liter/h hydrogen liquefier with LN precooling. The initial design calculations have been done but the detailed specifications are not complete. Work is proceeding on this project. Several other key design types have been identified and experiments are underway to test the main concepts, e.g., a charge/discharge circuit for a 9T magnet, operating at 0.5 Hz (efficiency is the question?).

With about 16 months of full-time operation on this program, I have learned a great deal but have not found anything that has dampened my enthusiasm for the eventual success of this program.

J. Barclay, LANL  
31 May 1983

## Notes on Apparatus

### Basic Research Equipment:

- |   |          |
|---|----------|
| 1. Magnetic susceptibility and typical result | Item #1  |
| 2. Magnetization and typical result           | Item #2  |
| 3. Heat capacity and typical result           | Item #3  |
| 4. Heat transfer and typical result           | Item #4. |

### Oxygen Production Possibilities

You will note from Figure B-11 from the rough draft of the Phase I KSC report (Item #5) that the hydrogen gas stream is completely separate from the magnetic refrigerator heat-transfer fluid which will be helium gas. The production of oxygen would be simple in that the cold helium gas streams from higher temperature stages could be split into two separate streams (or more) to cool incoming  $\text{CH}_4$ , incoming  $\text{CO}_2$ , and also to cool parasitic loads such as from shields, etc. The net thermal load at a particular temperature dictates the amount of magnetic material required for that stage (and higher stages) so given the loads as a function of temperature, a refrigerator can be designed to provide the cooling powers required. I can design a system like this as soon as I complete the 20-77 K  $\text{LH}_2$  refrigerator.

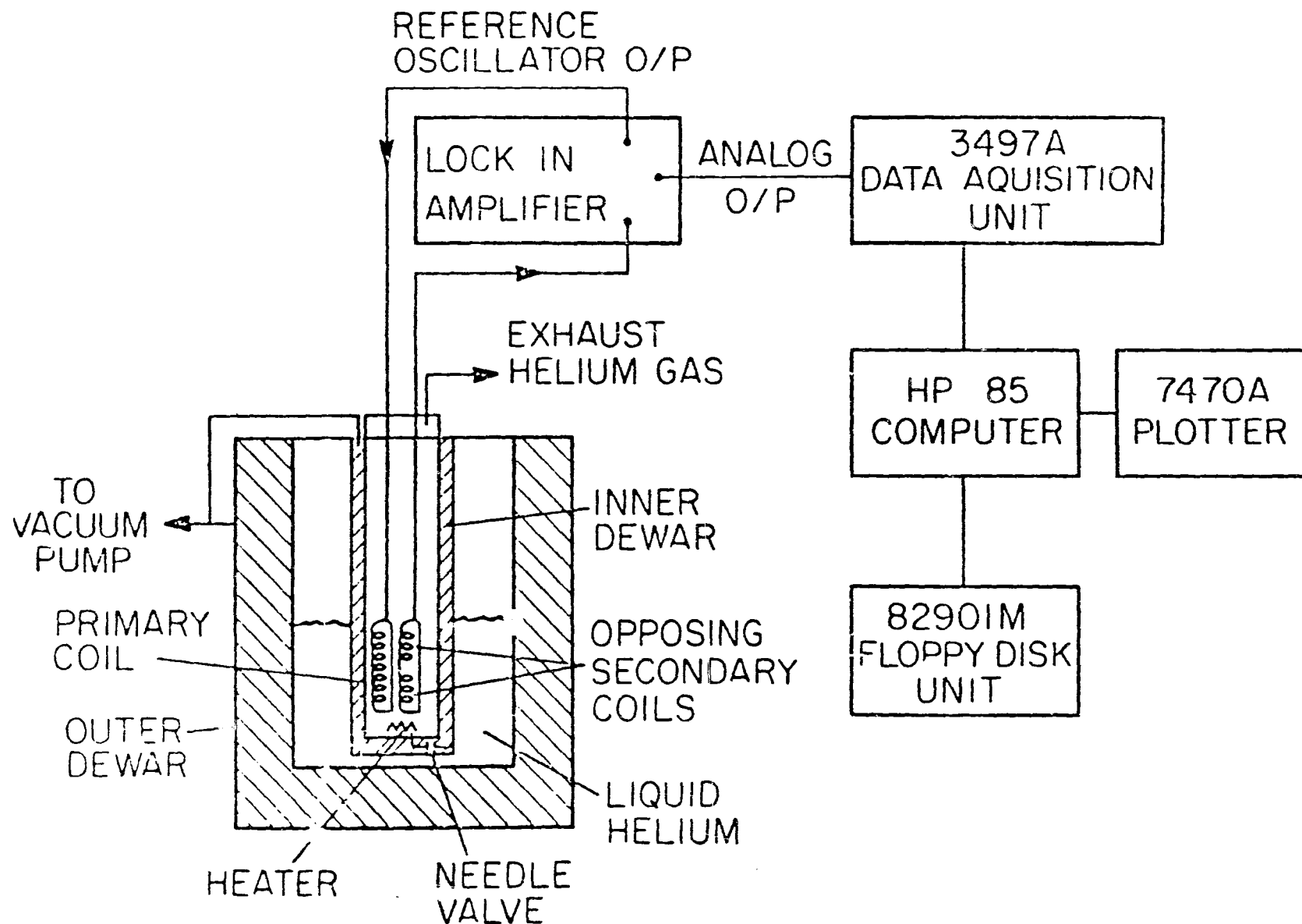


Figure B-1. A BLOCK DIAGRAM OF THE MAGNETIC SUSCEPTIBILITY APPARATUS



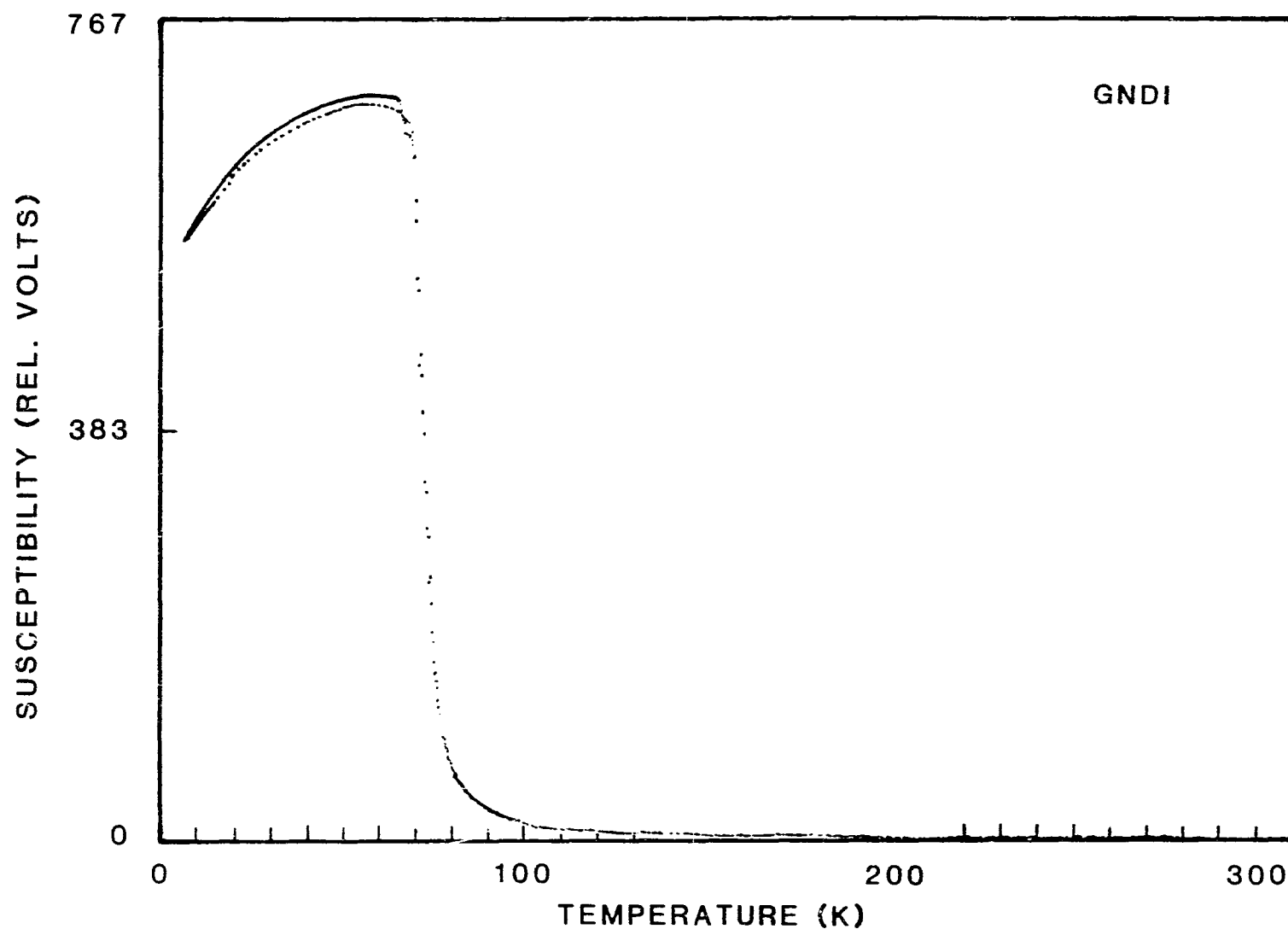


Figure B-2. THE RELATIVE MAGNETIC SUSCEPTIBILITY OF CdNi AS A FUNCTION OF TEMPERATURE. THE SHARP RISE IN SUSCEPTIBILITY IS A GOOD INDICATION OF FERROMAGNETIC ORDER. THE DUAL TRACE RESULTS FROM SWEEPING TEMPERATURE DOWN AND UP

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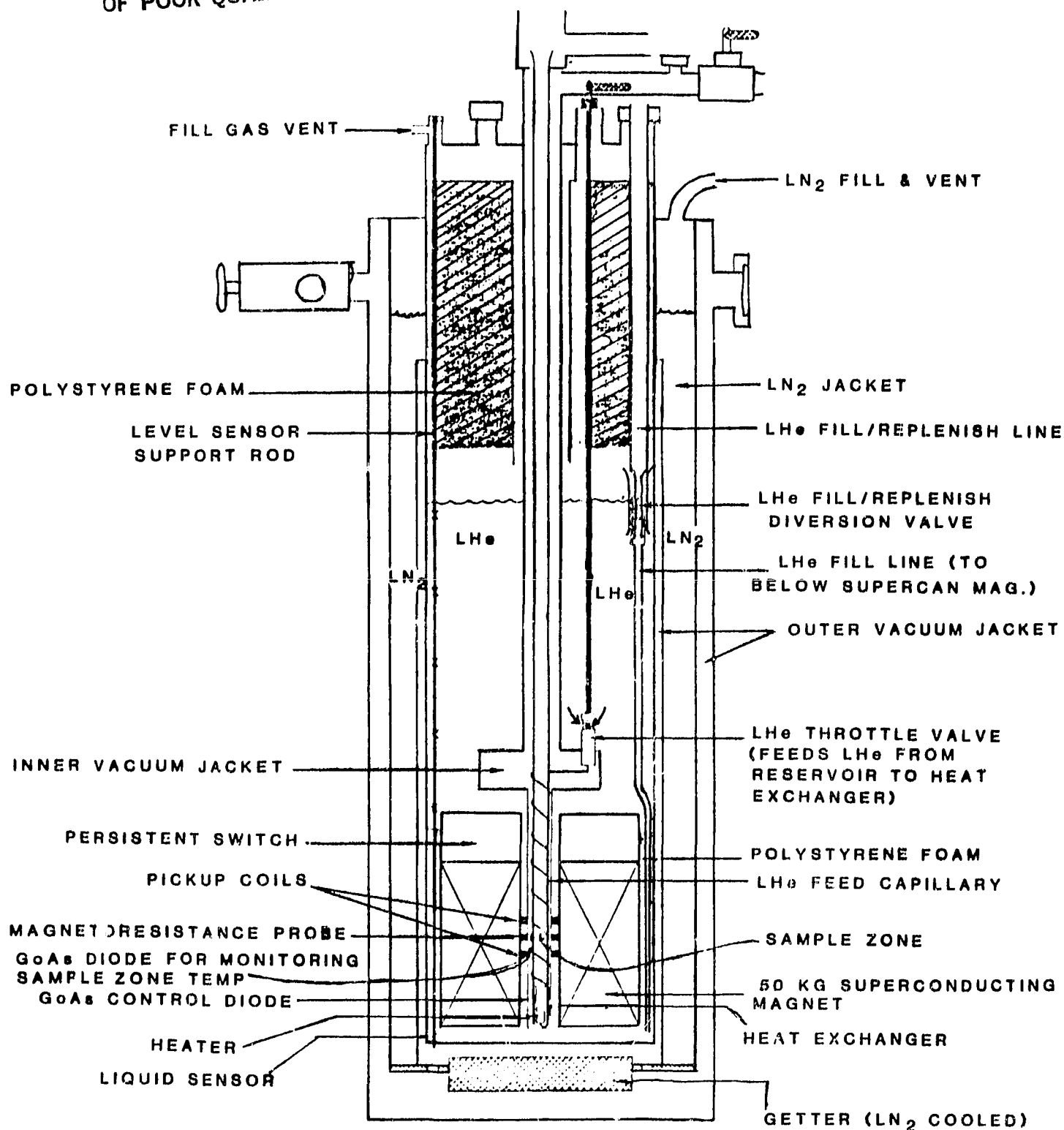


Figure B-3. VIBRATING SAMPLE MAGNETOMETER WITH VARIABLE TEMPERATURE PROBE IN FIELDS UP TO 8T

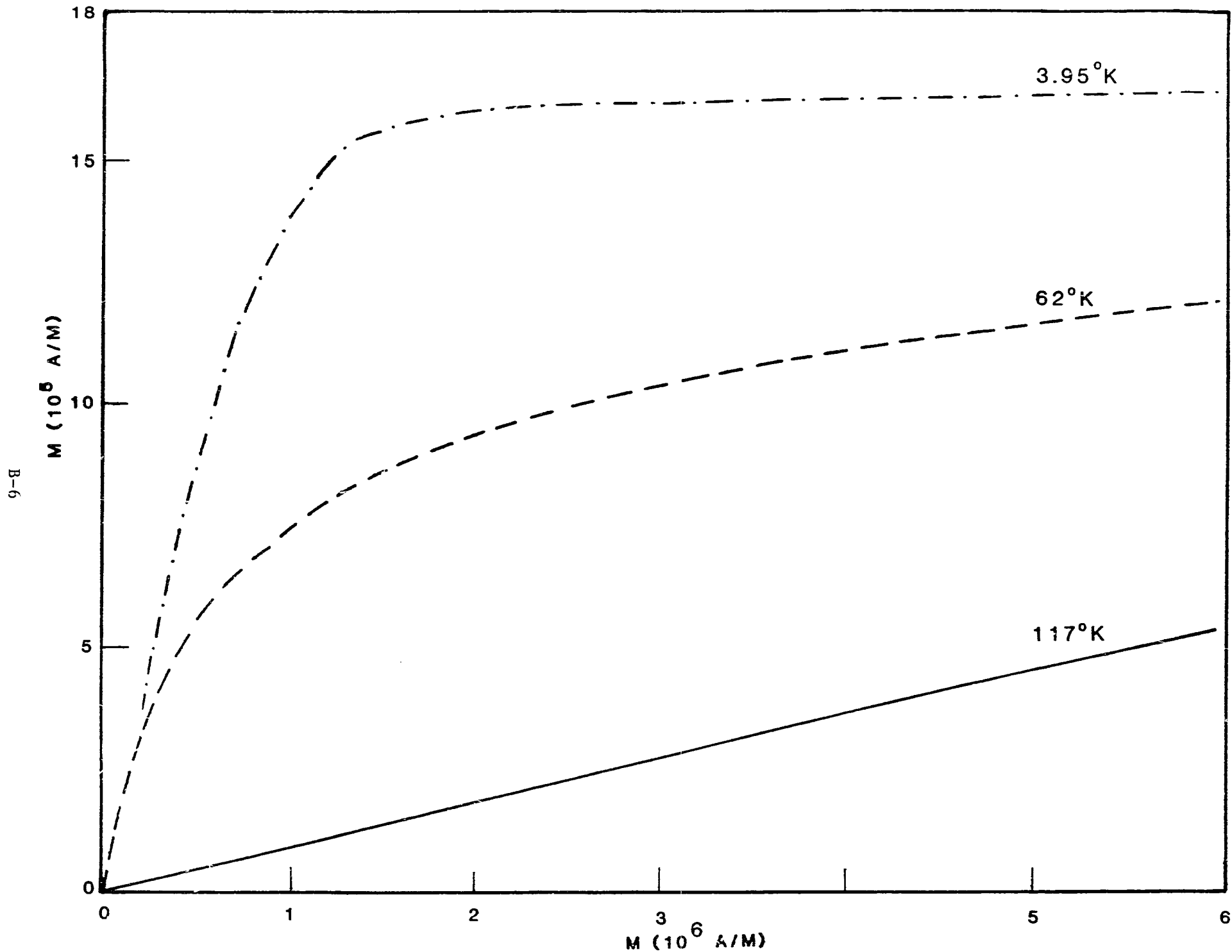


Figure B-4. MAGNETIZATION AS A FUNCTION OF APPLIED FIELD FOR GdNI AT THREE DIFFERENT TEMPERATURES

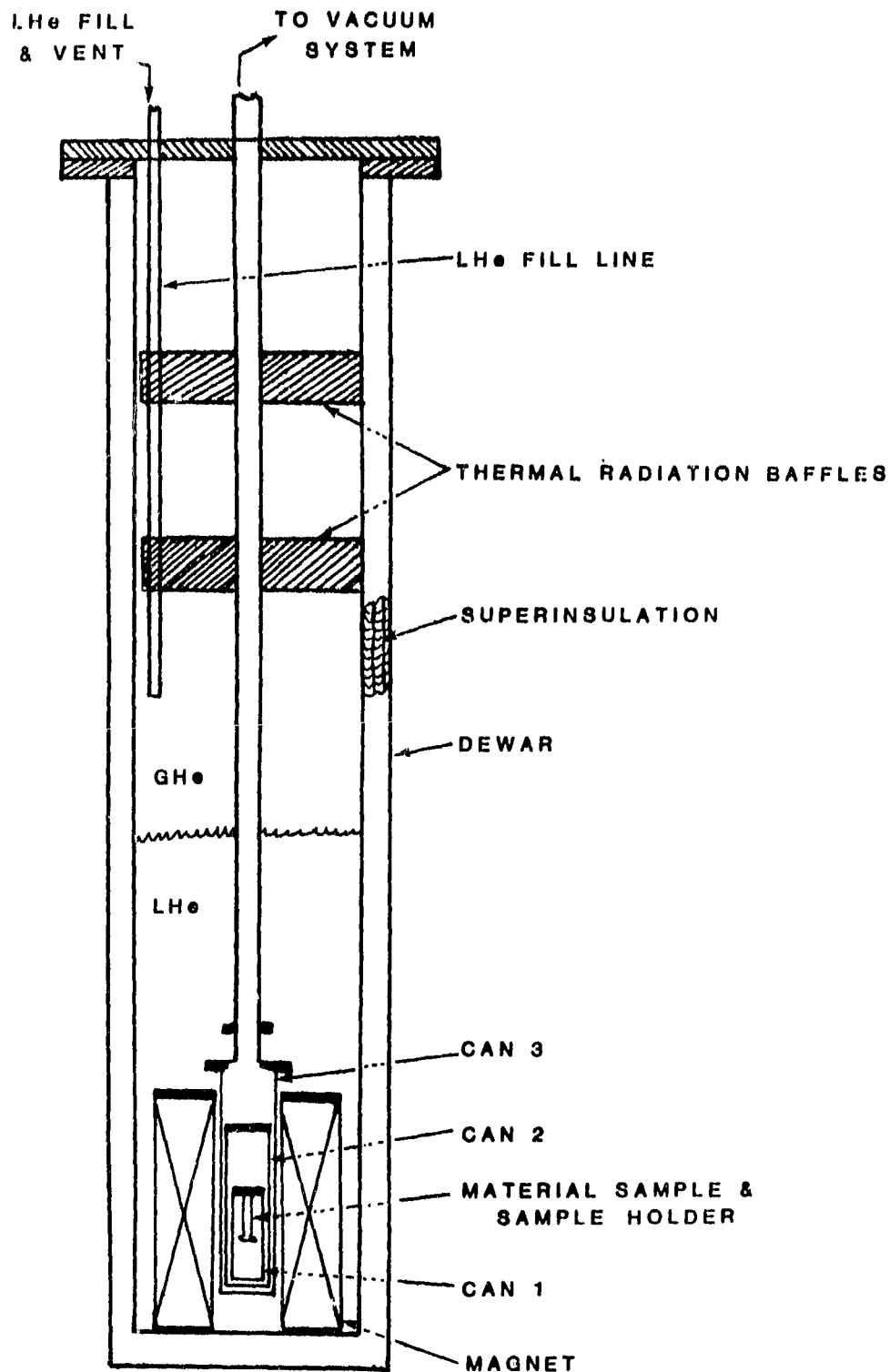


Figure B-5. DIAGRAM OF OVERALL HEAT CAPACITY-THERMAL CONDUCTIVITY APPARATUS.  
IT IS CAPABLE OF MEASUREMENTS FROM  $\sim 1\text{K}$  to  $300\text{K}$  IN MAGNETIC  
FIELDS UP TO  $9\text{T}$

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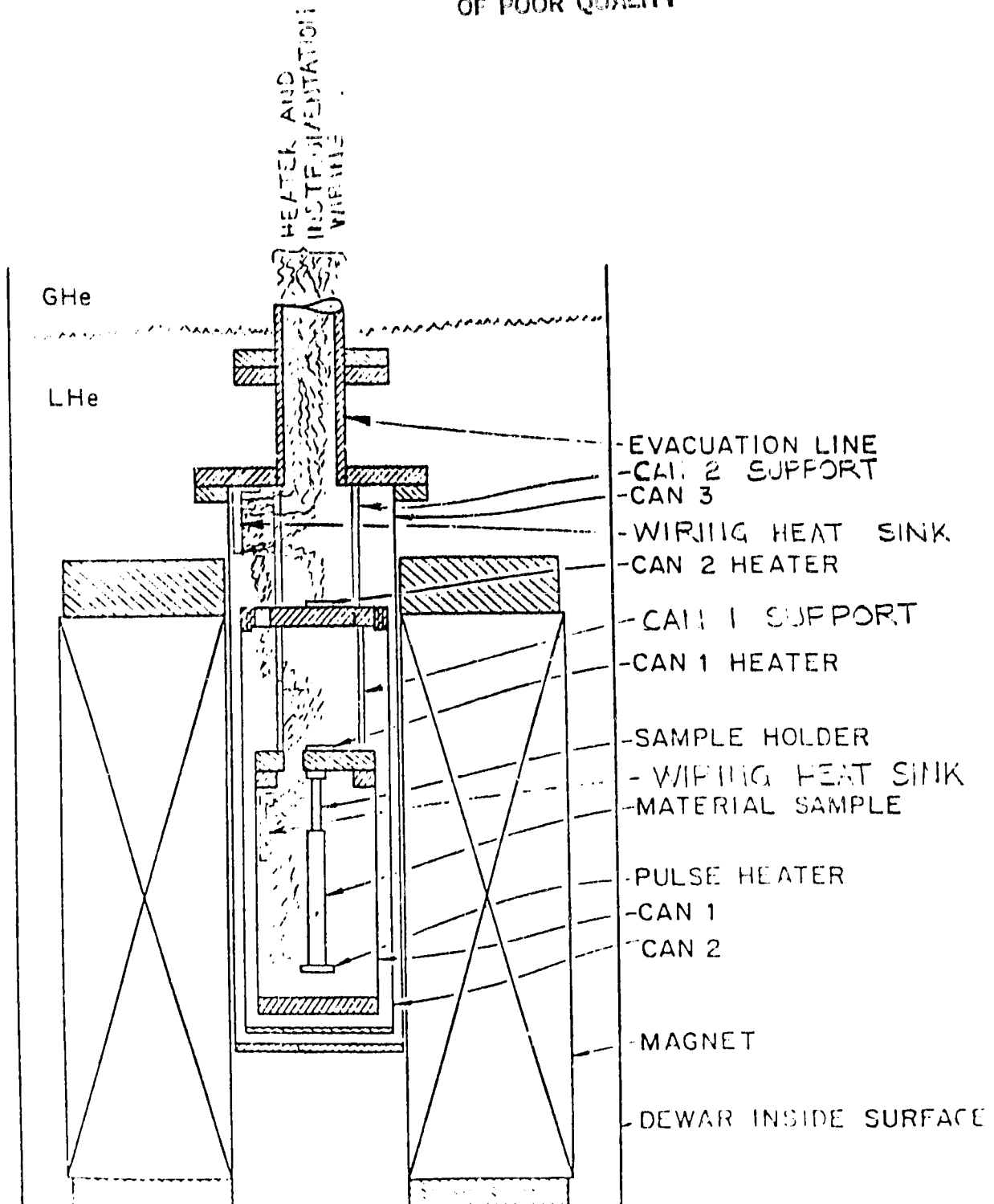
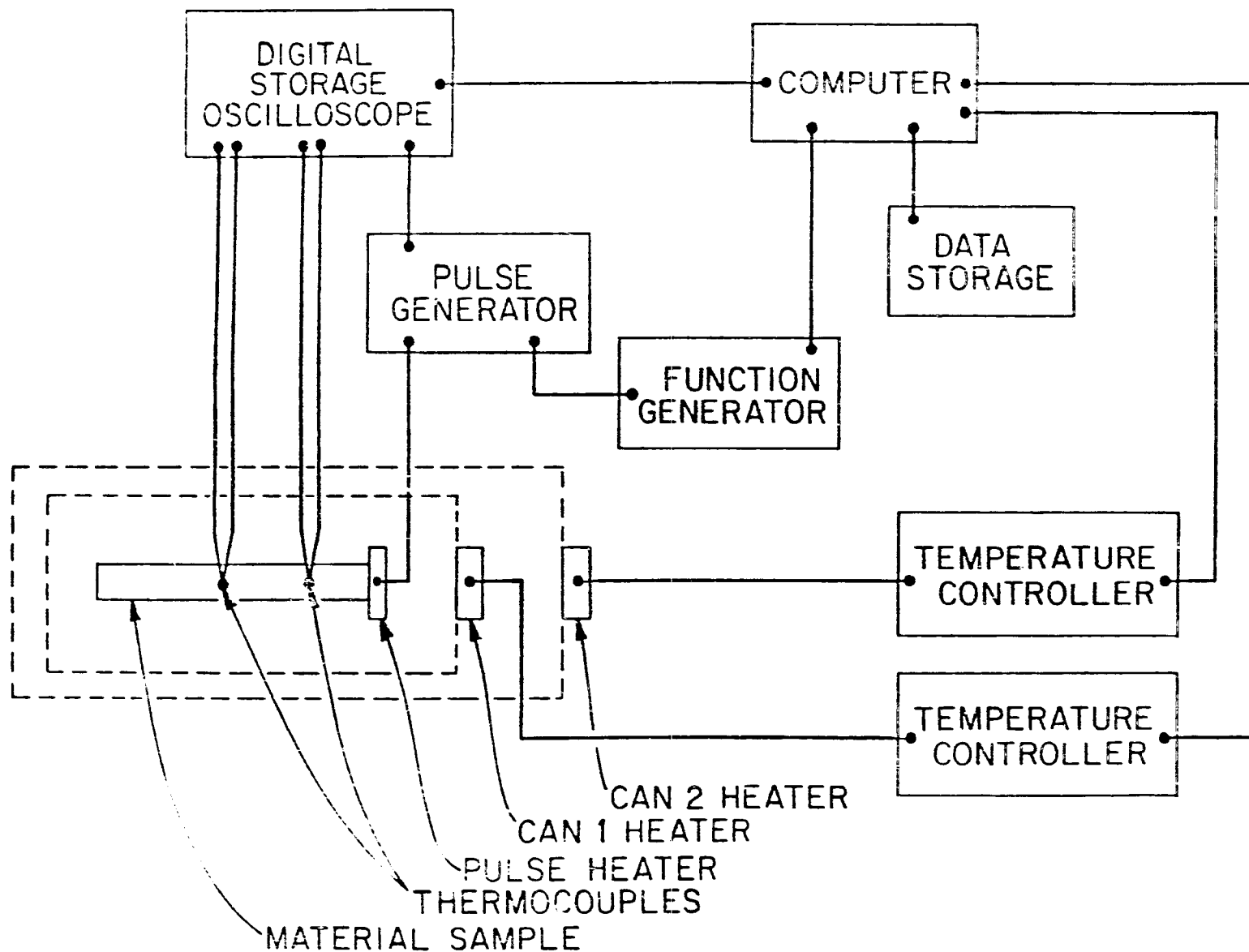


Figure B-6. A MORE DETAILED SCHEMATIC OF THE SAMPLE CHAMBER CONSTRUCTION. IT SHOWS THE THREE STAGES OF THERMAL ISOLATION BETWEEN THE SAMPLE AND LIQUID HELIUM



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Figure B-7. A BLOCK DIAGRAM OF THE INSTRUMENTATION SYSTEM FOR THE HEAT CAPACITY-THERMAL CONDUCTIVITY MEASUREMENTS

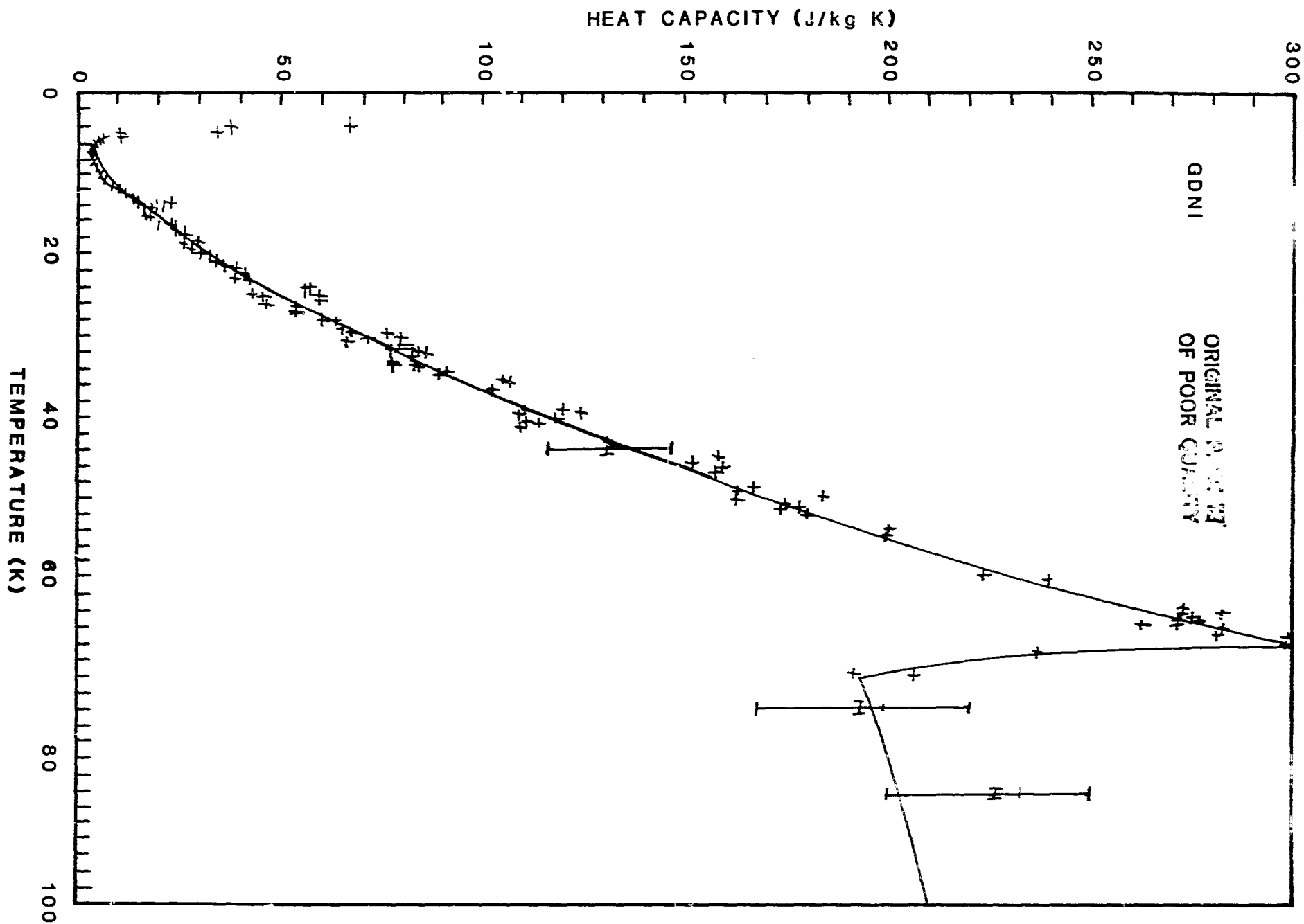


Figure B-8. HEAT CAPACITY AS A FUNCTION OF TEMPERATURE FOR GdNi. THE SOLID CURVE IS A POLYNOMIAL LEAST SQUARES FIT TO THE DATA

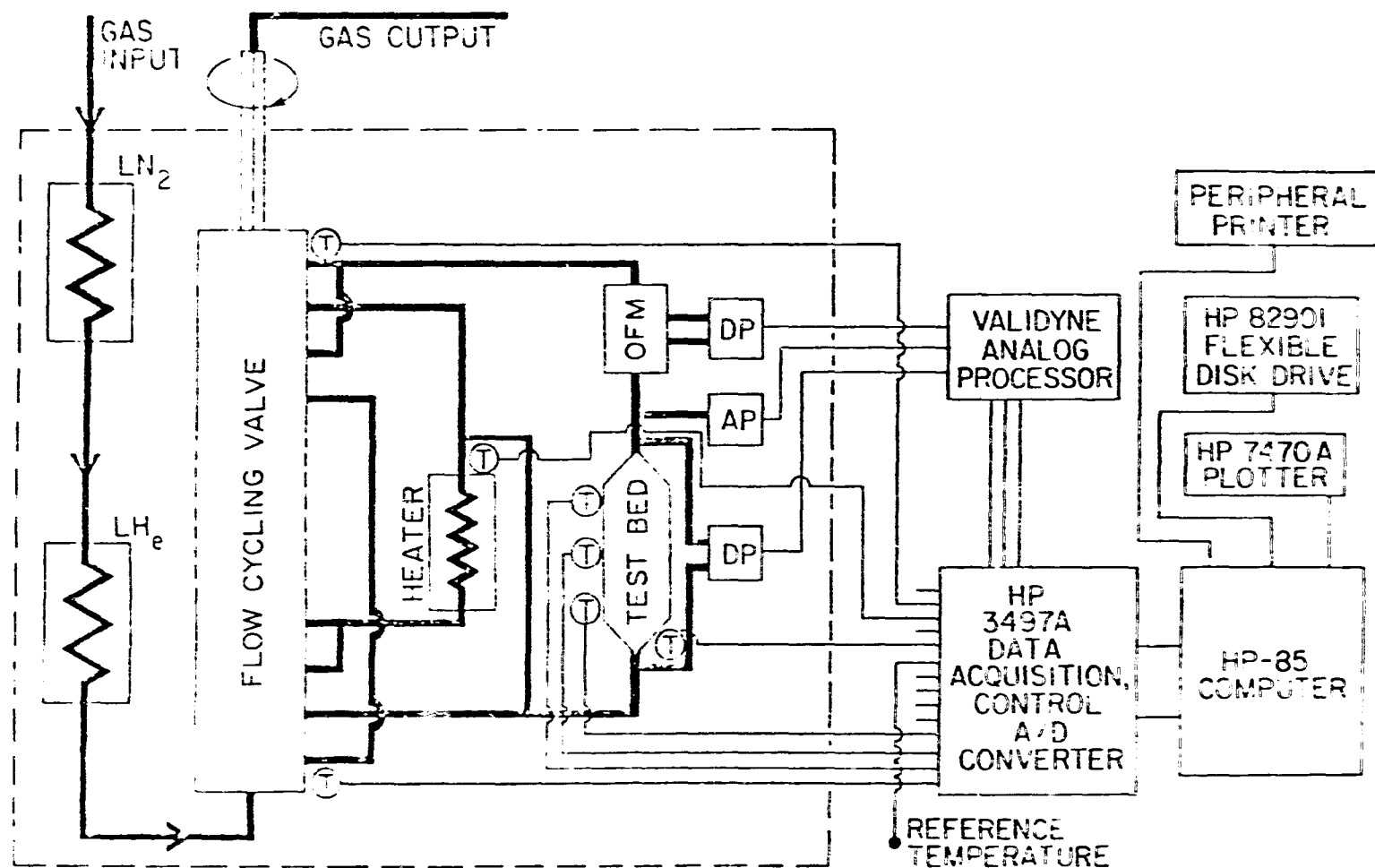


Figure B-9. A SCHEMATIC OF THE HEAT-TRANSFER AND PRESSURE-DROP APPARATUS. THE  $LN_2$  AND  $LHe$  POTS COOL THE GAS TO 4K AND THE HEATER CAN HEAT IT TO THE SELECTED TEMPERATURE. T INDICATES THERMOCOUPLE, DP INDICATES DIFFERENTIAL PRESSURE, AP IS ABSOLUTE PRESSURE, AND OFM IS AN ORIFICE FLOW METER. THE FLOW CYCLING VALVE CONTROLS THE FLOW AS SHOWN IN Figure B-14.



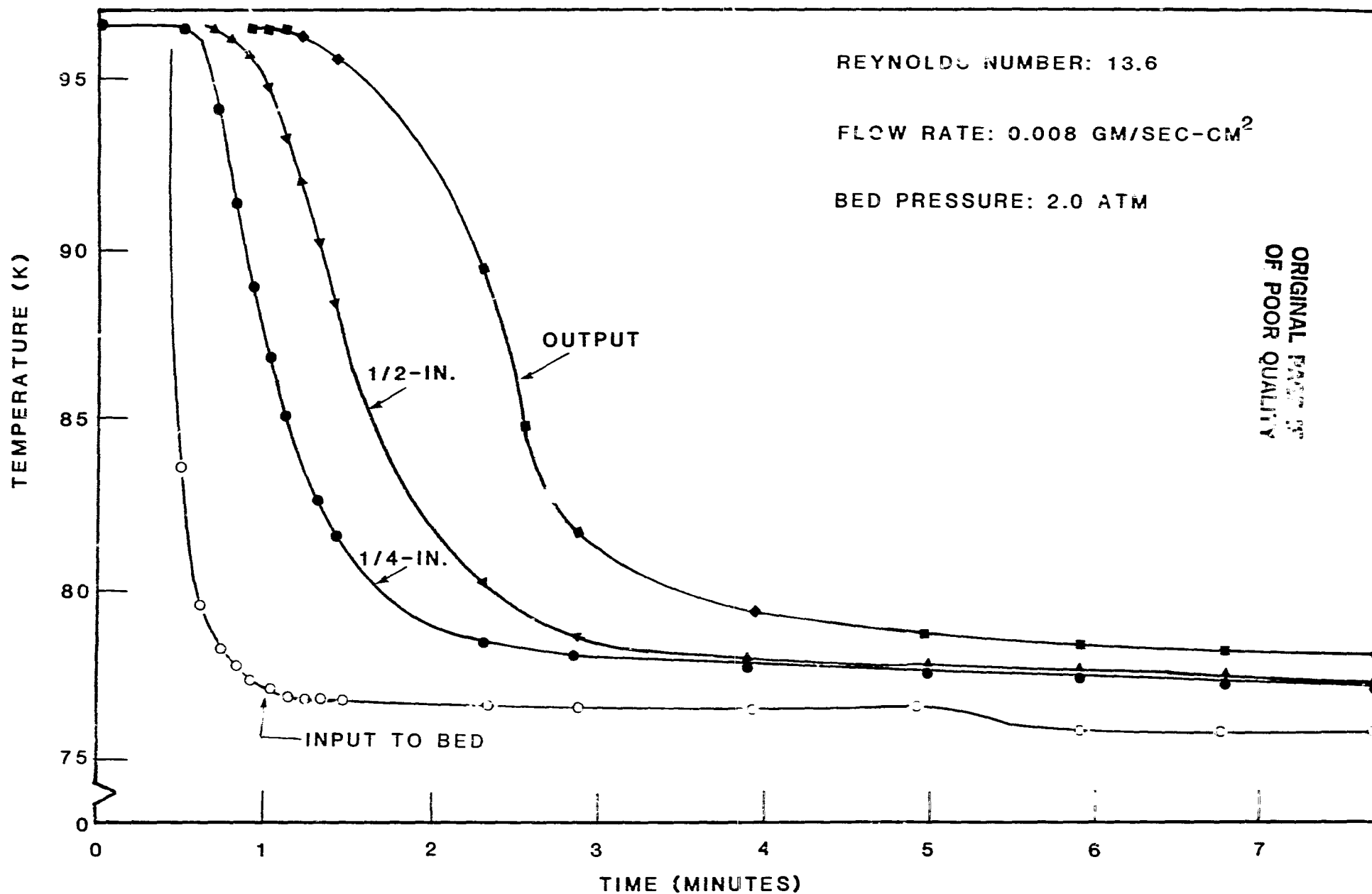


Figure B-10. TEMPERATURE PROFILES AT DIFFERENT POSITIONS IN A Pb-PARTICLE TEST BED. THE DISPERSION OF TEMPERATURE AS THE WAVE PROPAGATES THROUGH THE BED ALLOWS DETERMINATION OF THE THERMAL CONDUCTIVITY AND LONGITUDINAL THERMAL

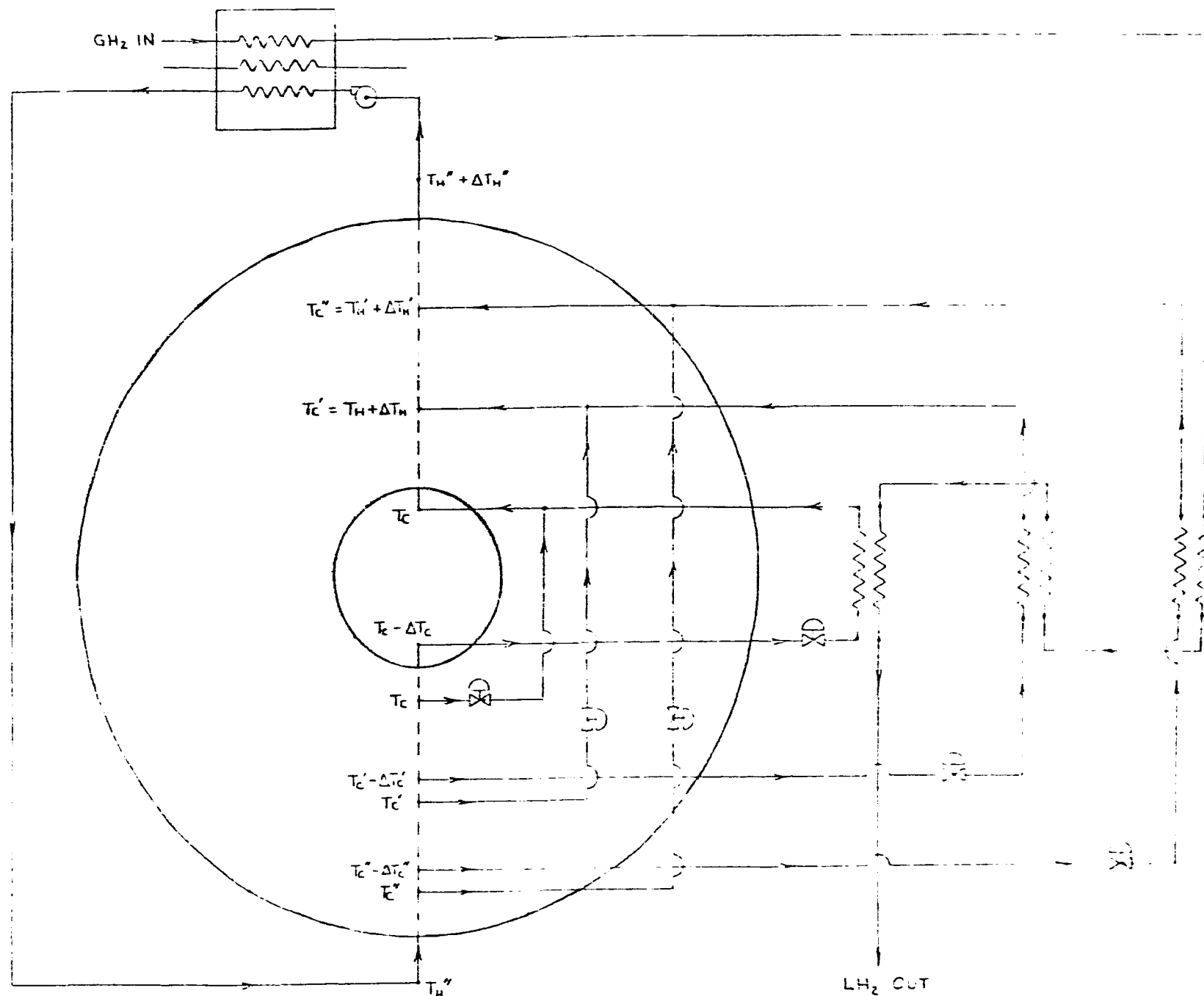


Figure B-12. A MULTISTAGE WHEEL, ACTIVE MAGNETIC REGENERATIVE REFRIGERATOR FOR LIQUEFYING HYDROGEN

APPENDIX B-2

Assessment of Practical Application of Magnetic Refrigeration in the Liquefaction of Hydrogen

Charles R. Baker  
Linde Division  
Union Carbide Corporation

## ASSESSMENT OF PRACTICAL APPLICATION OF MAGNETIC REFRIGERATION IN THE LIQUEFACTION OF HYDROGEN

The magnetocaloric effect (MCE) has been known for half a century. Its application in paramagnetic heat pumping to produce temperatures below those previously attainable was first suggested independently by both Giauque and Debye and has been used extensively ever since in research laboratories to obtain temperatures approaching absolute zero. The validity of the technique is well established and is not subject to question.

The topic of interest is the use of MCE in a magnetic refrigerator and its application to the liquefaction of hydrogen on a commercial scale. The development of the magnetic refrigerator has been pursued by Dr. John A. Barclay of the Los Alamos National Laboratory (LANL) for several years. Many theoretical analyses have been published (References B-1 through B-5) concerning the performance of this device and all studies have suggested that the magnetic refrigerator represents a potential breakthrough with regard to thermodynamic performance. Efficiencies which are in the order of double those attainable via gas compression/expansion cycles appear to be possible. Because hydrogen liquefaction is an energy intensive process, and the cost of this energy is a substantial portion of the cost of producing liquid hydrogen, an improvement in operating efficiency of this magnitude would mean a significant reduction in the cost of liquid hydrogen.

However, all analyses have been made only on the concept and mathematical models thereof; it is not known that any working models exist. Although Dr. Barclay has addressed and evaluated a number of recognizable contributions to process inefficiency and has pointed out a number of problem areas requiring considerable development effort, there is no assurance that all contingencies have been foreseen. This is the nature of R&D. Only by building and operating an actual working device of appropriate scale can one be assured that his predictions are valid.

Dr. Barclay points out (Reference B-1) that one of the critical elements of the process is the regenerative heat exchange between the magnetic material and the working fluid. Very high thermal efficiencies must be obtained if serious reductions in overall process efficiency are to be avoided, and it must not be obtained at the expense of high frictional pressure loss. The necessary efficiencies are within the state-of-the-art by the use of porous matrices but must be considerably greater than is the current commercial practice using brazed aluminum plate and fin exchangers.

Finally, Dr. Barclay examines (Reference B-5) the hydrogen liquefaction process using magnetic refrigeration. There are differences between a refrigerator and a liquefier and these differences require modifications in the refrigerator design which are both advantageous and disadvantageous. It appears that a practical hydrogen liquefier would be a staged device of several refrigerators in series. The staging would improve the effectiveness of the refrigerators but would introduce irreversible losses in the heat exchange between the working fluid and the feed/product stream. The problem of ortho-para conversion must also be addressed. Most of the conversion occurs below 100 K and imposes a large additional heat load on the liquefier. A staged liquefier implies staged conversion which is less efficient than equilibrium conversion. Liquefaction processes which feature a near approach to equilibrium conversion are in current commercial practice.

There are also a myriad of not-so-minor mechanical problems which must be solved, particularly with the rotary wheel concept. Problems such as seals, leakage, flow control, insulation, and fluid pumping, among others, are certain to exist and must be overcome on a practical basis.

The preceding comments are not to be interpreted as a denigration of the magnetic refrigerator concept but rather to emphasize that there must be a considerable development effort before the concept can be converted to a commercial reality. The traditional development route of model fabrication and testing and prototype construction leading to small commercial units for specialized applications will require time. Given enough incentive, sufficient resources could be brought to bear to reduce the duration of the development period considerably, but this is not likely to occur in the present energy environment. It is foreseen, then, that the magnetic refrigerator will not play a significant role in the large-scale liquefaction of hydrogen in the current decade and probably not within this century. However, its promise is sufficiently great that the presently-foreseen problems will eventually be solved.

#### References Cited in Appendix B-2

- B-1. Barclay, J.A., "An Analysis of Liquefaction of Helium Using Magnetic Refrigerators," Los Alamos National Laboratory Report LA-8991, December 1981.
- B-2. Barclay, J.A. and Steyert, W.A., "Materials for Magnetic Refrigeration Between 2 K and 20 K," Cryogenics, p. 73, February 1982.
- B-3. Barclay, J.A., "Use of a Ferrofluid as the Heat Exchange Fluid in a Magnetic Refrigerator," J. Appl. Phys. 53(4), 2887, April 1982.
- B-4. Barclay, J.A. and Stewart, W.F., "The Effect of Parasitic Refrigeration on the Efficiency of Magnetic Liquefiers," Proceedings, 17th IECEC, Paper No. 829198, August 1982.
- B-5. Barclay, J.A., "Can Magnetic Refrigerators Liquefy Hydrogen at High Efficiency?" paper presented at the 20th Joint ASME/AIChE National Heat Transfer Congress, Milwaukee, WI, 2-5 August 1981.

APPENDIX C

PHYSICAL AND ECONOMIC PARAMETERS FOR CONVENTIONAL LH<sub>2</sub> PLANTS

Charles R. Baker  
Linde Division  
Union Carbide Corporation

January 31, 1983

Mr. William J.D. Escher  
E:F Technology, Inc.  
1405 N. U.S. 27  
P.O. Box 189  
St. Johns, MI 48879-0189

Dear Bill:

This package of information confirms that which I sent to you earlier via Telecopy. The work which you originally requested is only partially complete, although well along. Some of the information is presented both graphically and in tabular form although I expect that you will want to redraft the graphs for final formal use for both appearance and consistency with your other artwork.

The facility described is a complete hydrogen liquefaction unit, self-sustaining except for electricity, cooling water and low pressure steam, and includes a nitrogen liquefier to produce liquid as well as cold nitrogen gas to meet refrigeration needs at the 80-100K level. There is also a small nitrogen-only air separation plant to provide makeup nitrogen so that it need not be imported from an outside source. This is more economical than purchasing trucked-in liquid.

The electricity, cooling water and steam are utilities assumed to be available at battery limits. If water and steam are unavailable, a cooling tower and small boiler will have to be provided at additional cost.

The hydrogen feedstock is assumed to be that produced electrolytically in the units described by the Teledyne papers. The purity of this hydrogen is very good and poses no problems for the purification equipment that is provided with the liquefier. In fact, we can probably handle considerably higher impurity levels and I will be investigating exactly what the upper limit may be.

I have given you turndown power requirements to 50% of design point. I have trouble going much below this capacity because of surge limitations on certain of the centrifugal

Mr. William J.D. Escher  
E:F Technology, Inc.

- 2 -

January 31, 1983

compressors. The best way around this is probably using dual-train 50% units. However, this would produce some increase in the cost of the facility. The problem involves only the nitrogen liquefier and the air separation plant. Dual-train compression has been provided for the hydrogen liquefier.

In response to your question concerning liquefaction of by-product oxygen, I think that this feature can readily be designed into the nitrogen liquefier unit already being provided in support of the hydrogen liquefier. At 20 TPD of liquid hydrogen capacity, there would be 175 TPD of oxygen gas available for liquefaction. This would nearly double the size of the N<sub>2</sub> liquefier. Space shuttle launch requirements based upon NASA's Polygeneration solicitation are 12 TPD of liquid hydrogen which equates stoichiometrically to 95 TPD of liquid oxygen. A nice feature of the electrolytic unit is that it produces stoichiometric quantities of hydrogen and oxygen.

I've checked briefly into the cost of liquid hydrogen storage tanks. An approximate figure for a 400,000 gallon tank would be about \$2,000,000 today. I'll be checking this further.

There was also the question about personnel requirements for the plant. I have not addressed this question yet but this information is easily developed.

All costs are based on first quarter 1983 dollars.

I have addressed, here, all of the work items which I understood that you assigned to me. If there are any omissions or any items overlooked, please let me know. I expect to be available for any questions or further effort in support of the project.

Best regards,



C. R. Baker

CRB/fmm  
Attachments

cc: Mr. A. W. Bailey



CRACKER  
OF POOR QUALITY

HYDROGEN FEED REQUIREMENT

20 TPD HYDROGEN LIQUEFIER

Flow, CFH-NTP	350,000
Pressure, psig	75
Temperature, °F	90
Composition *	≥ 99.999% (tentative)
Water Content	Saturated at 75 psig and 90°F

\* Lower purity level may be acceptable.  
Is being investigated.

NTP = 70°F & 1 atmosphere

Cost is for battery limits, complete hydrogen liquefier installed, including:

1. Hydrogen Liquefier Unit
2. Nitrogen Liquefier Supporting Unit
3. Air Separation Plant to Provide Nitrogen Makeup
4. Foundations
5. Buildings for Hydrogen Compressors, Control Room, Maintenance and Electrical Switchgear.
6. Instrumentation/Computer Control
7. Site Work, Grading, Drains, Sewers, Fire Protection, Paving, Potable Water, Fencing.

Availability of cooling water at battery limits is assumed; no cooling tower has been provided.

Existence of electrical substation is assumed outside battery limits.

Storage tank for liquid hydrogen is not included.

Availability of 15 psig saturated steam at battery limits is assumed.

**TOTAL COST**

**HYDROGEN LIQUEFIER**

<u>Capacity TPD of Liquid Hydrogen</u>	<u>Cost (1Q 83)</u>
8	\$12,500,000
15	19,500,000
20	24,000,000
25	28,300,000

# UTILITY REQUIREMENTS

## HYDROGEN LIQUEFIER

ORIGINAL PAGE 10  
OF POOR QUALITY

LIQUEFIER CAPACITY, TPD	<u>8</u>	<u>15</u>	<u>20</u>	<u>25</u>
ELECTRICITY, KW	4030	7260	9490	11800
COOLING WATER, GAL/MIN	2300	4200	5500	6800
15 PSI STEAM, LB/HR	280	525	700	875

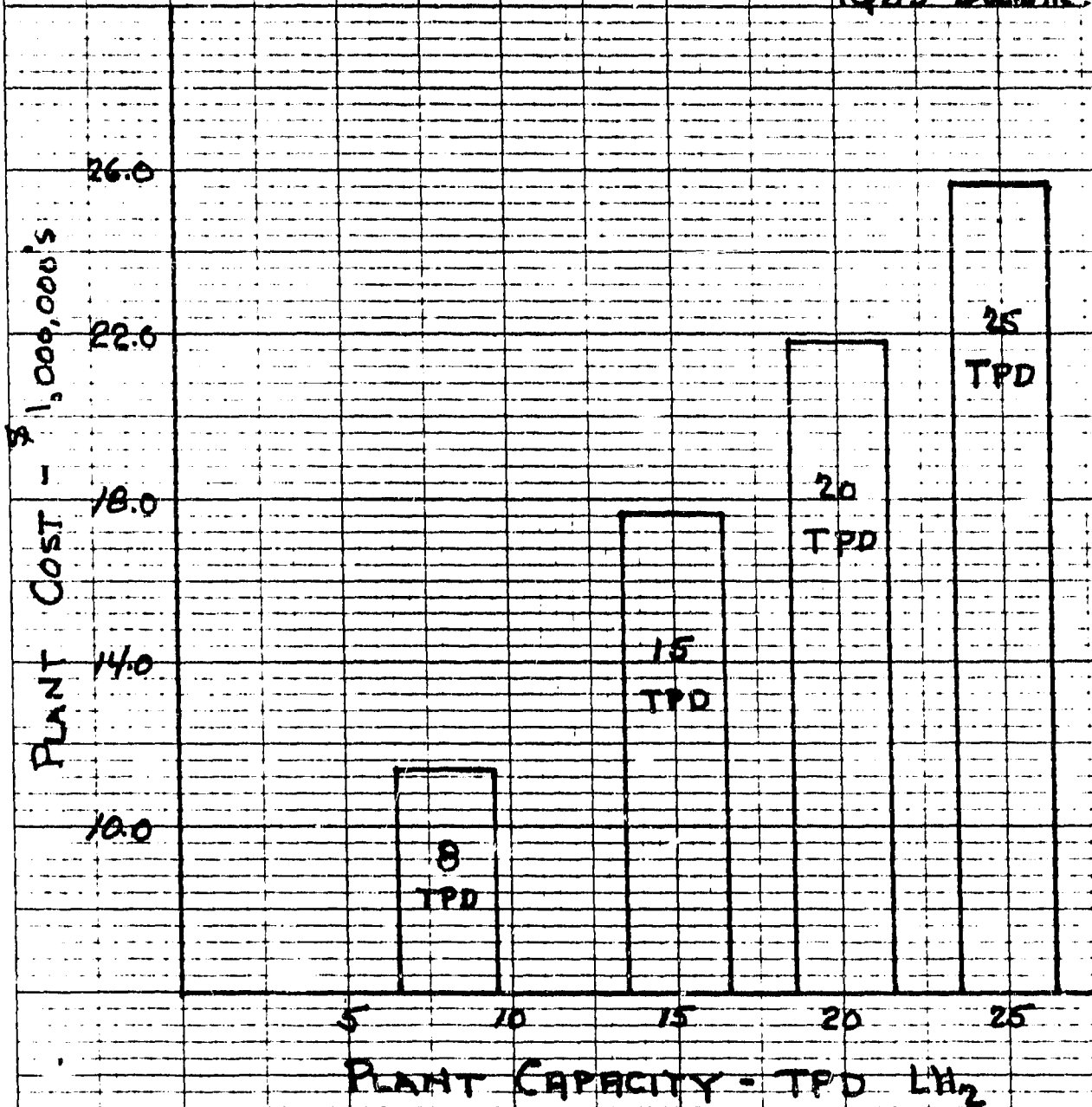
## TURNDOWN POWER REQUIREMENT

### 20 TPD H<sub>2</sub> LIQUEFIER

<u>PLANT CAPACITY</u>		<u>POWER</u> <u>KW</u>	<u>UNIT POWER</u> <u>KWH/LB LH<sub>2</sub></u>
<u>%</u>	<u>TPD LH<sub>2</sub></u>		
110	22	10,390	5.67
100	20	9,490	5.69
90	18	8,635	5.76
80	16	7,805	5.85
70	14	6,985	5.99
60	12	6,160	6.16
50	10	5,320	6.38

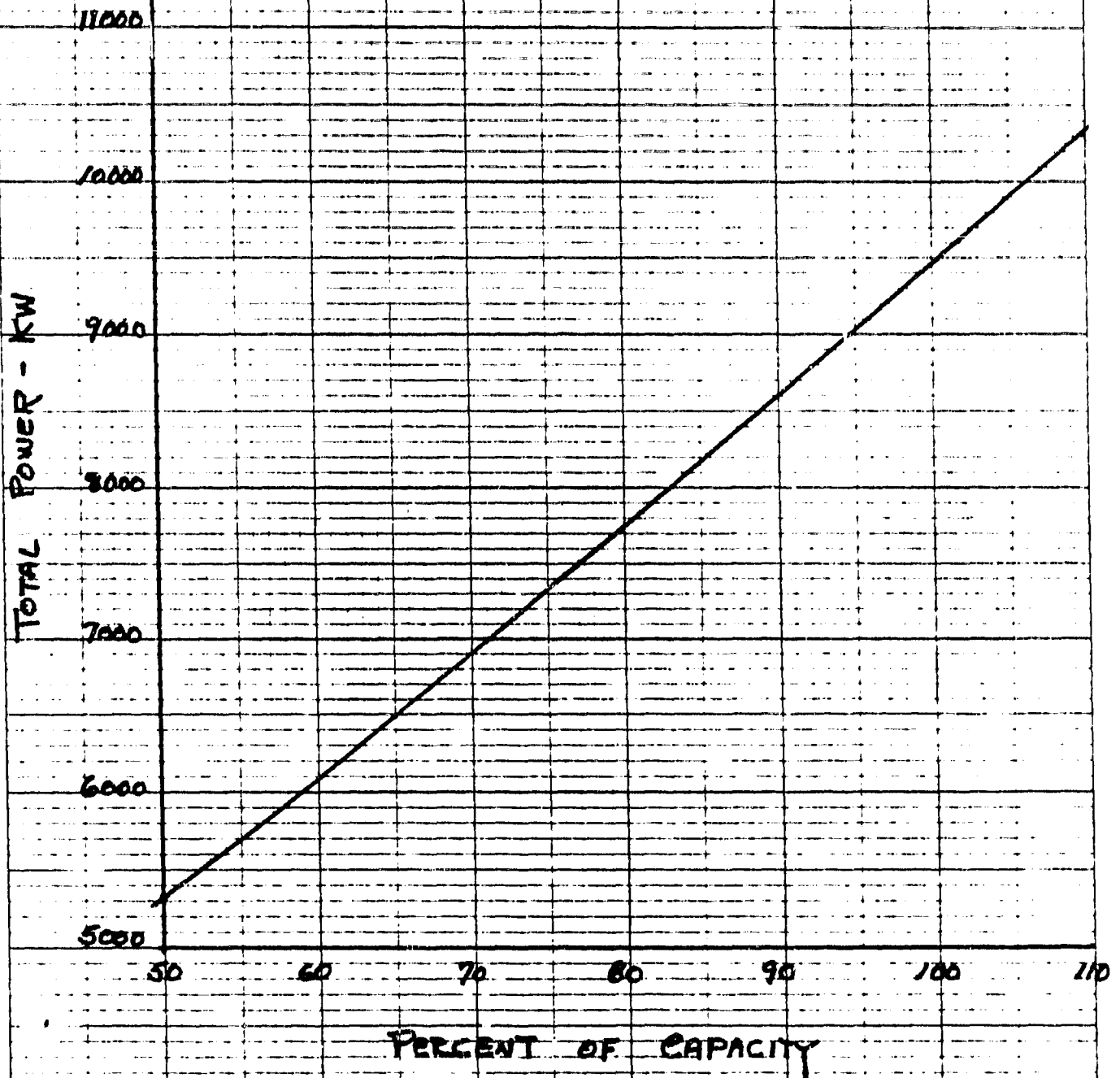
# CAPITAL COST OF HYDROGEN LIQUEFIERS

1983 DOLLARS



TOTAL ELECTRICAL POWER  
REQUIREMENT - 20 TPD

LIQUID HYDROGEN





Union Carbide Corporation  
Linde Division  
P.O. Box 44  
Tonawanda, New York 14150  
Telex 91 311

ORIGINAL  
OF 10

February 4, 1983

Mr. William J.D. Escher  
E:F Technology, Inc.  
1405 N. U.S. 27  
P.O. Box 189  
St. Johns, MI 48879-0189

Dear Bill:

I now have additional information to forward to you which either adds to or supersedes that presented in my letter of January 31.

First of all, the feed hydrogen purity. The adsorption purification system provided with the hydrogen liquefier is capable of handling up to 50 ppm impurities in the hydrogen feed, including oxygen and nitrogen. For higher impurity levels, additional purification capacity would have to be provided.

Concerning the cost of liquid hydrogen storage tanks, I have a firm current quotation from CB&I of \$1,600,000 for a 400,000 gallon spherical, vacuum insulated tank. Foundations would add another \$20,000 but otherwise the cost is on an installed basis. The cost of tanks of different sizes have historically shown a linear dependence upon capacity. Thus, a 200,000 gallon tank would be expected to cost \$800,000 and a 600,000 gallon size would cost \$2,400,000.

Plant personnel requirements are shown on the attached sheet. The list was selected to provide not only the requirements for plant operation but also to provide at least two persons in attendance at all times for personnel safety. This pretty much represents a fixed roster and would not vary with plant capacity over the 8-25 TPD capacity range. The plant manager might not be kept too busy, however, and he might be able to devote only half-time to this plant if there were other responsibilities available to him such as the management of another plant in same locality.

Operation and maintenance costs are tabulated on an attached sheet for all four plant capacities. Included are labor, supervision, administration and overhead, operating supplies and maintenance supplies and parts. They run from 3.4 to 5.8% of plant investment.

Mr. William J.D. Escher  
E.F. Technology, Inc.

- 2 -

February 4, 1983

Concerning plant turndown, if dual train nitrogen compressors are provided for the nitrogen liquefier, then by shutting down one train of compressors, the plant could be turned down to 25% of design capacity. Further turndown should be a complete plant shutdown. The added investment for the dual train nitrogen compressors is estimated to be \$190,000 or 0.8% of plant investment for the 20 TPD capacity. The same percentage of investment can be used for other plant capacities. I have also added a page showing turndown power requirements to 25% of design capacity for the 20 TPD liquefier.

Restart of the plant after a modest shutdown (e.g. overnight) should not be time consuming. The cold boxes are very well insulated and very little warmup of equipment will occur in this period. Most of the time would be spent in going through the checklist for startup procedure and readying the plant for operation. Operation at full capacity can usually be achieved within an hour. I have also sketched out a block flow diagram and included a copy to give a better appreciation of the facility.

I hope this answers all your questions and trust you had a successful presentation at the recent briefing

Best regards,



C. R. Baker

CRB/fmm  
Attachments

PERSONNEL REQUIREMENTS

20-TPD HYDROGEN LIQUEFIER

- 1 - Plant Operator - 3 shifts per day  
To man control room and operate facility.
- 1 - Instrument/Control Operator - 1 shift per day  
To maintain instruments and computer in  
operation and calibration.
- 1 - Maintenance Mechanic - 2 shifts per day  
To maintain plant in mechanical repair
- 1 - Production Supervisor - 1 shift per day  
To supervise plant and instrument/control  
operation.
- 1 - Maintenance Supervisor - 1 shift per day  
To supervise plant maintenance operations.
- 1 - Plant Manager
- 1 - Secretarial Assistant



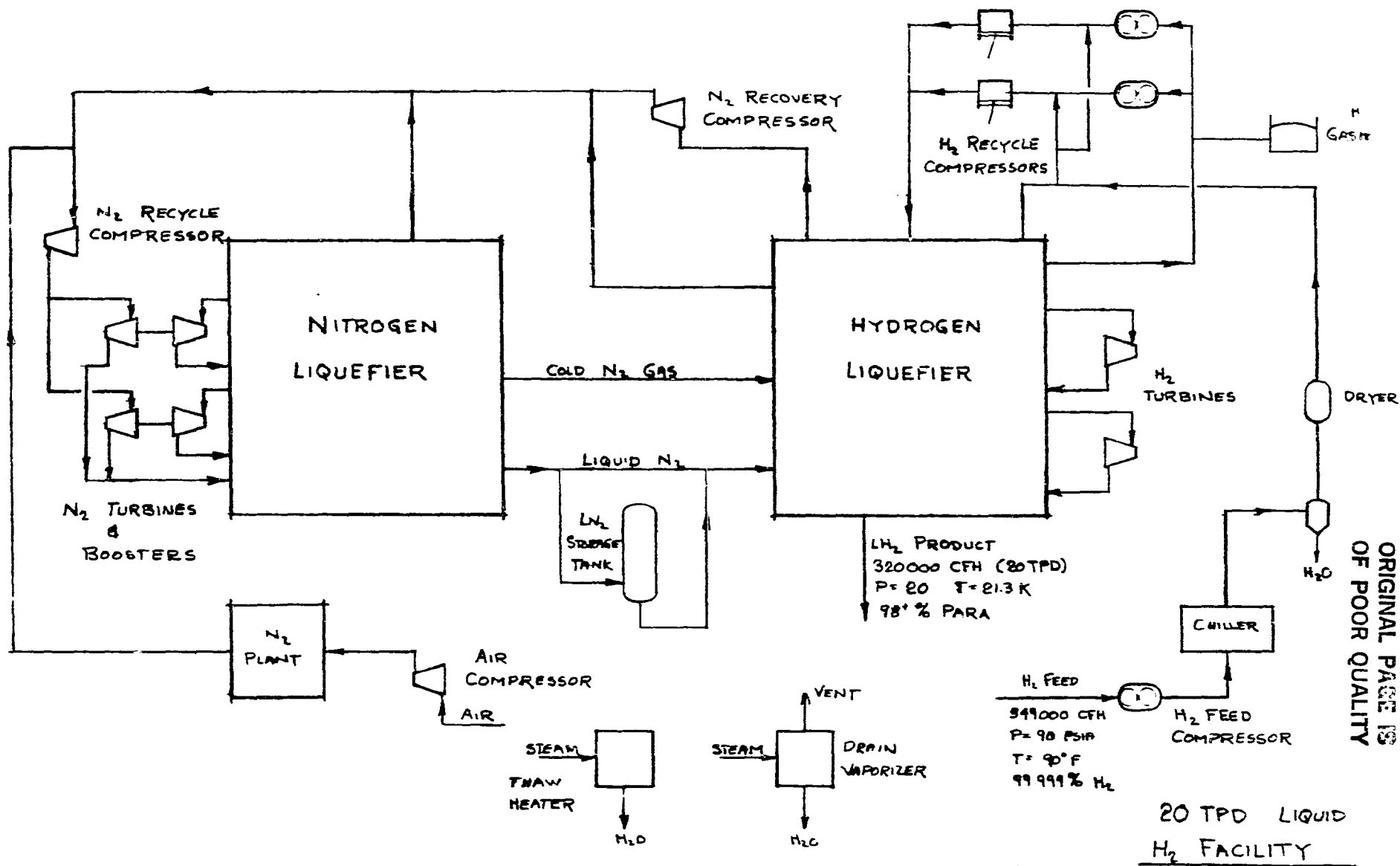
OPERATING AND MAINTENANCE COSTS  
HYDROGEN LIQUEFACTION FACILITY

<u>Plant Capacity</u> <u>TPD LH<sub>2</sub></u>	<u>Annual</u> <u>Operating and</u> <u>Maintenance Costs</u>
8	\$730,000
15	840,000
20	910,000
25	970,000

TURNDOWN POWER REQUIREMENT  
 20 TPD H<sub>2</sub> LIQUEFIER  
ONE COMPRESSOR TRAIN IN OPERATION

<u>PLANT CAPACITY</u>		<u>POWER KW</u>	<u>UNIT POWER KWH/LB H<sub>2</sub>-</u>
<u>%</u>	<u>TPD LH<sub>2</sub></u>		
40	8	4020	6.03
30	6	3220	6.44
25	5	2810	6.74

C-13





Union Carbide Corporation  
Linde Division  
P.O. Box 44  
Tonawanda, New York 14150  
Telex 91-311

February 17, 1983

Mr. William J.D. Escher  
E:F Technology, Inc.  
1405 N. U.S. 27  
P.O. Box 189  
St. Johns, MI 48879-0189

Dear Bill:

This will confirm the information on oxygen liquefaction which I provided to Ray Tison via telephone on Feb. 15, 1983.

The cost of tanks for liquid oxygen is considerably less than for liquid hydrogen. NASA's solicitation on their polygeneration facility places the quantity of liquid hydrogen required for one shuttle launch at 180 tons, or 610,000 gallons. The stoichiometric equivalent of liquid oxygen is 1430 tons, 300,000 gallons or 35,000,000 SCF. Our designation for a tank of this capacity is LR-35 and it's cost is \$480,000 or \$1.60 per gallon. If you would like a different size tank, a scaling exponent of 0.56 will apply over the range of 200,000 to 600,000 gallons. You will also need a \$60,000 foundation which is in addition to the \$480,000 purchase price.

The oxygen liquefaction unit can be integrated into the nitrogen liquefier which produces refrigeration for the hydrogen liquefier. The estimate is based on increasing the nitrogen liquefier capacity and heat exchanging the liquid nitrogen with the oxygen. The following table summarizes the power requirement and investment for oxygen liquefaction capability for the four different hydrogen liquefier sizes.

LH <sub>2</sub> Plant Size TPD	O <sub>2</sub> Liquefaction Rate TPD	Power KW	Cost \$ Million
8	63.5	1450	2.1
15	119.0	2600	3.0
20	158.7	3400	3.6
25	198.4	4200	4.1

Mr. Willaim J.D. Escher  
E:F Technology, Inc.

- 2 -

February 17, 1983

Operation of the oxygen liquefier will require no additional personnel. The manpower roster which I specified in my Feb. 4 letter will be able to handle this additional activity.

Best regards,



C. R. Baker

CRB/fmm

cc: A. W. Bailey



Union Carbide Corporation  
Linde Division  
P.O. Box 44  
Tonawanda, New York 14150  
Telex 91 311

ORIGINAL  
OF FOUR

March 10, 1983

Mr. William J.D. Escher  
E:F Technology, Inc.  
P.O. Box 189  
St. Johns, MI 48879-0189

Dear Bill,

I have read with interest the proposed paper on photo-voltaic hydrogen by you and your associates. I would say that you have done an outstanding job and the material presented clearly shows the depth of background in solar energy systems possessed by your organization. I don't have sufficient familiarity with such technology to make meaningful comments on most of the material but I do have some remarks on one or two items with which I am familiar.

Your liquid hydrogen requirement of 6 million lb per year for the space shuttle is somewhat less than the level which I understand is needed. According to NASA's solicitation 10-2-0150-2 for the Polygeneration Study, a single shuttle launch will use 612,600 gallons or 181 tons of liquid hydrogen. At 18 launches per year, this comes out to be 6.52 million pounds, or about 9% greater than your figure.

I also don't think that your 8 TPD plant is quite large enough. At a uniform launch rate, and assuming 5% plant outage for maintenance and repair, a liquefaction capacity of 9.4 tons/day would be required. NASA points out that they are contemplating a non-uniform launch schedule and that a maximum effective interval of 15 days between launches should be used for plant sizing, placing it at 12 tons/day.

You have also indicated that you would be providing two weeks' storage for both liquid oxygen and liquid hydrogen. At 181 tons of LH<sub>2</sub> consumption per launch and LH<sub>2</sub> production at 8 tons/day, 22 days' storage would be needed to meet shuttle launch requirements. Two weeks' storage is not enough.

These capacity differences really relate to differences in concept; whether you want to project an ideal portrayal or whether you want to be more realistic. I would readily agree with either route.

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Mr. William J.D. Escher  
E:F Technology, Inc.  
Page 2

March 11, 1983

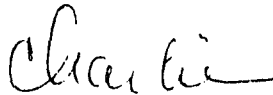
On page 5, water and product gas mains are laid in a common trench. For safety reasons, this may not be advisable. Open trenches have a way of collecting flammable materials, often oil or grease. A leak in the oxygen piping could result in a severe fire. A closed trench, while keeping out combustible matter, would pose a hazard should there be leakage in both hydrogen and oxygen lines. I would see no problem if the oxygen gas main, at least, were buried. An alternative would be to place both H<sub>2</sub> and O<sub>2</sub> gas mains in above-ground pipe racks at low elevation so as not to shade the collector array.

In the same paragraph, gas pressures are assumed to be 10 psi at the central collection point. I assumed the hydrogen feed to the liquefier to be 75 psig while the oxygen was available at 35 psig. I'm not certain that these differences have been addressed with respect to power requirements.

I have also received some literature from John Barclay on his magnetic refrigerator and am reviewing it. My present, but not necessarily final, perception of his technology is that it seems to have high potential but it will be quite some time before it can be developed to the point where it becomes a reliable method for producing refrigeration for large-scale industrial plants. It will obviously have first use in small specialized applications.

I also expect to take some vacation time over the Easter holidays and will not be available from March 28 until April 7. I will be fully available for any consultation both before and after this period.

Best regards,



C. R. Baker

CRB/fmm

June 29, 1983

Mr. Robert J. Sprafka  
E:F Technology, Inc.  
1405 N. U.S. 27  
P.O. Box 189  
St. Johns, MI 48879-0189

Dear Bob:

This will confirm the information concerning hydrogen losses which I provided you verbally over the phone earlier this week.


The original block flow diagram for the 20 TPD hydrogen liquefier showed that a 349,000 cfh feedrate was required to produce 320,000 cfh of liquid hydrogen product. The difference of 29,000 cfh (8.3% of the feedstock) represents leakage losses, mostly through the shaft seals for the compressor and turbines as well as through valves.

By implementing the anti-leakage measures described in Section 9 of NASA report CR-145077, "Study of the Potentials for Improving the Efficiency and Economics of Liquid Hydrogen Produced from Coal", July, 1976, I estimate that total leakage losses can realistically be reduced to 8,000 cfh or 2.5% of the feedstock rate. This would be distributed roughly as follows:

Compressor Shaft Seals	-	45%
Turbine Shaft Seals	-	30%
Cold Box	-	25%

The leakage rate may be scaled proportional to plant capacity so that for a 10 TPD liquefier, the expected leakage rate would be 4,000 cfh. The cost of providing these anti-leak measures is estimated to cost \$100,000 for a 10 TPD liquefier capacity. This is an economically attractive investment compared with the value of the hydrogen saved.

Best regards,



C. R. Baker

CRB/fmm



## APPENDIX D

### Hydrogen From Renewable Energy: Photovoltaic/Water Electrolysis as an Exemplary Approach

Dr. Robert J. Sprafka  
Mr. Raymond R. Tison  
Mr. William J.D. Escher  
E:F Technology, Inc.

CONFIDENTIAL  
OF 100-100-100

Paper presented at the 20th Space Congress,  
Cocoa Beach, Florida, 27 April 1983

HYDROGEN FROM RENEWABLE ENERGY: PHOTOVOLTAIC/WATER  
ELECTROLYSIS AS AN EXEMPLARY APPROACH

Dr. Robert J. Sprafka  
Mr. Raymond R. Tison  
Mr. William J.D. Escher

E:F Technology, Inc.  
St. Johns, Michigan

ABSTRACT

Potential large-scale production of liquid hydrogen and liquid oxygen from water using photovoltaic solar energy conversion at the NASA Kennedy Space Center is examined in this paper. The example non-optimized, stand-alone facility described produces about 5.76 million pounds of liquid hydrogen per year, and 8 times that much liquid oxygen, which could support about 18 Space Shuttle launches per year.

A 100-MWp flat-plate photovoltaic array, measuring 1.65 square miles, is required. The full array is made up of 249 modular 400-kWp arrays with several electrical/gas product "grids" considered. Hydrogen and oxygen are produced with either dispersed or central water electrolyzers. A central product liquefaction facility with 2-weeks' storage is provided.

Estimated liquid hydrogen product costs, leveled over a 20-year facility life, range from about \$3.00 to \$7.50/lb liquid hydrogen, depending mainly on the cost of installed photovoltaics. (The range examined was \$.50 to \$2/Wp.) At about \$1.50/Wp, a liquid hydrogen conventional/non-fossil cost parity would seem to be achievable over the period 1990 to 2010.

**Keywords:** liquid hydrogen, liquid oxygen, solar energy, photovoltaics, water electrolyzers, liquefiers, Space Shuttle propellants.

SUMMARY

This paper addresses the large-scale, stand-alone production of liquid hydrogen and oxygen via water electrolysis powered by electricity from a photovoltaic array located on or near the NASA-Kennedy Space Center (KSC). Liquefaction of product gases is accomplished by a conventional plant powered by a dedicated photovoltaic array with battery storage.

The system was sized to produce on the order of 6 million lb/year of liquid hydrogen ( $5.76 \times 10^6$ ), and  $46 \times 10^6$  pounds/year of liquid oxygen are produced as well. For perspective, this equates to full liquid hydrogen/liquid oxygen logistics support for the Space Shuttle Program operating at about 18 launches per year.

A total photovoltaic array power rating of about 100 MWp is required based on recorded insolation received at KSC. The resulting array power split is 67.6 MWp for water electrolyzer facility operation and 32 MWp for the hydrogen and oxygen liquefier operation. Hydrogen and oxygen production from water occurs only when the photovoltaic array is active under direct and diffuse illumination by the sun. However, product liquefaction proceeds around the clock with nighttime energy supplied from battery storage charged photovoltaically during the day.

Using estimated capital costs and operating and maintenance expenses, leveled costs are calculated for liquid hydrogen and liquid oxygen produced over the 20-year facility life. Costing is based on standardized guidelines for electric utility facilities by the Electric Power Research Institute (EPRI).

BACKGROUND

At present, KSC's liquid hydrogen demands are met by conventional industrial gas supply means quite similar to other merchant hydrogen customers. Specifically, liquid hydrogen is purchased under contract from Air Products & Chemicals, Inc. The hydrogen is produced by the conventional natural gas (methane) steam reforming process and liquefied at Air Products' New Orleans facility. From there, it is transported by KSC-owned-and-operated 13,000-gallon tractor-trailer units. Recently, trial runs have begun on rail tank car delivery as a way of supplementing over-the-road delivery.

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Natural gas, the basic feedstock, is a depletable fossil fuel resource subject to near-term cost escalations and unavailability. Accordingly, NASA planners have initiated studies of alternative sources of liquid hydrogen by way of opening up possible options for ensuring long-term continuation of supplies. The continued use of natural gas will, of course, be a competitive option.

Another approach under consideration at KSC is on-site coal gasification in a "Polygeneration" facility, i.e., one providing several useful products in addition to hydrogen. Yet another category of options is non-fossil production of liquid hydrogen. Based on a competitive procurement, KSC awarded a contract to a study team led by E:F Technology, Inc., in late-September 1982 (Ref. 1). To address this possibility, this paper was developed from information gathered/analyzed for this contract (see Acknowledgments).

This paper addresses one of the nearer-term, KSC-sited, solar energy-operated alternatives: a photovoltaic-based (solar cell)/water electrolysis, liquid hydrogen/liquid oxygen production system. This system was identified earlier by E:F as one of four solar/hydrogen production approaches which were commercializable by the year 2000 (Ref. 2). As next discussed, the example system to be described is not optimized nor is it necessarily related to those one or two systems called out to be studied in some depth by the contractor team.

The basic objective of this presentation is to illustrate one specific approach for providing non-fossil-produced liquid hydrogen and oxygen as an alternative to today's fossil-based production means. Being illustrative and not reflecting trade-offs and "fine tuning" advantages, this exemplary system demonstrates basic feasibility while suggesting the order of product costs which may be expected, in a generic sense, from solar-based hydrogen production.

### SYSTEM REQUIREMENTS

The following basic guidelines were adopted in configuring the exemplary system:

- Photovoltaic solar energy conversion to be used on a stand-alone basis (no utility power or other energy inputs)
- KSC facility location (insolation data used is that measured by the Florida Solar Energy Center at Cape Canaveral)
- Technology and estimated costs applicable to the 1987-1992 time period
- Nominally, the Space Shuttle's 18 launches/year to be fully supported; this

equates to a nominal 6 million lb/year of liquid hydrogen use (final facility sizing:  $5.76 \times 10^6$  lb/yr)

- Coproduct oxygen also to be collected and liquefied (leading to some excess liquid oxygen over Shuttle needs as met by the liquid hydrogen produced).

### TECHNICAL APPROACH

The basic makeup of the exemplary system is shown in block diagram form in Figure 1. Displayed here are subsystems operating in a series flow-through manner. These are:

- Photovoltaic Array--provides direct conversion of received sunlight, both direct and diffused, into d-c electricity
- Water Electrolyzer--provides electrochemical separation of the constituents of water using photovoltaic electricity into molecular hydrogen and oxygen as ambient temperature gases
- Product Liquefiers--converts the ambient-temperature gaseous electrolyzer products into cryogenic liquid hydrogen and oxygen, as used in the Space Shuttle.

Associated with these subsystems, various kinds of energy and product storage are provided, e.g., batteries and gaseous and liquid storage.

### SYSTEM SIZING AND LAYOUT

In order to produce six million pounds of hydrogen gas per year, 294.3-MW hours/day of energy must be stored in the form of hydrogen. Using sunlight at 5 to 6 hours/day of full-sun equivalent implies that a system of 50- to 60-MW peak power (without considering losses in the process) is required.

To date, no photovoltaic system of this size has been constructed, although at least one is planned--with the initial few Megawatts of capacity under construction (Ref. 3). Including the liquefier facility, the system discussed here will occupy approximately 1.5 square miles. Again for perspective, space availability at a facility such as KSC should not be a problem.

Typically, the output of existing and planned PV installations has been a-c electricity. With hydrogen as the product, several unconventional system approaches are possible, each having its own set of advantages/disadvantages. Those approaches covered in this paper rely on a basic building block: a 400-kWp PV sub-array or module (to be described later). The method of linking the required 170 or so modules leads to several possibilities to be further discussed:

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- PV module + inverter + a-c grid + central rectifier + central electrolyzer + gaseous product storage
- PV module + d-c busbar + central electrolyzer + gaseous product storage
- PV module + distributed electrolyzer gas mains + gaseous product storage.

The liquefier itself will be powered by the first option using its own "dedicated" array. Distributed battery storage provides 24 hour/day operation (liquefiers only).

## THE 400-KWP PV MODULE

Following more or less conventional practice, PV panels which are 3.125 meters high are arranged in rows 10 meters apart as shown in Figure 2. The panels are mounted on a horizontal "torque tube" permitting rotation along an east-west axis. Throughout the year, the tilt angle of the panels is changed several times to keep the insolation nearly normal to the panel surface at solar noon. An example of such a tilt schedule is given in Table 1. Using values from this table (used at Florida Solar Energy Center, FSEC, 28.5°N latitude), at winter solstice, the 10-meter spacing together with a scheduled 48° tilt angle results in some shading of panels at sun altitudes less than 16°. Unshaded operation is then possible from 8:30 a.m. to 3:30 p.m. At the 24° tilt angle associated with the equinoxes (mid-March, mid-September), no shading occurs since at sun altitudes less than 16° (which the panels would block), the sun is behind the south-facing collectors. No shading occurs when the sun is further north (e.g., Summer).

Table 1. TILT ANGLE AND APPLICABLE DATES

Tilt in Degrees	Date Range
48	3 Nov - 9 Feb
40	10 Feb - 4 Mar
32	5 Mar - 24 Mar
24	25 Mar - 13 Apr
16	14 Apr - 7 May
8	8 May - 7 Aug
16	8 Aug - 30 Aug
24	31 Aug - 20 Sep
32	21 Sep - 10 Oct
40	11 Oct - 2 Nov

In order to determine the optimum dimensions for the 400-kWp module, i.e., the number of rows and the corresponding row length, we assume rectangular arrays were laid out with the d-c power tie-point at the rough geometric center of the rectangle. The cost of copper conductors was to be minimized. The number of rows was varied from 1 (1,600 m long) to 160 (10 m long) each. The PV panels

were taken to be 3% efficient on a panel area basis—a number which combines cell efficiency and geometric packing fraction.

Copper requirements were calculated for each configuration so that there exists at most a 1-V drop from each 500-V submodule of the 400-kWp sub-array to the power-tie point. Copper costs per peak watt were calculated using cable and wire at 5¢/pound installed. The results are shown in Figure 3. It can be seen that a clear minimum exists at 13 rows of collectors, implying 123 m long rows.

Collection at 500-V was arrived at after considering worker safety, good inverter efficiencies (if used), and electrolyzer matching without dependence on d-c to d-c converters. Higher voltages would reduce the copper requirement but would detract from PV-electrolyzer matching. (See next section.) PV cell operating experience at 1,000 V and higher has resulted in arcing from the cell through the potting materials to ground. It is noted that the most recent Block V photovoltaics government buy specifies 1,000-V operation. Lower collection voltage (than 500-V) would lead to excessive copper cabling as well as lower a-c inverter efficiencies.

Thus, as shown in Figure 4, the 400-kWp sub-array module is physically 123 x 130 m in extent and provides d-c at 499 V and 800 A. The 499 V reflects a power loss of 800 W out of the total produced—an 0.2% loss.

Based on available PV cost predictions, e.g., Reference 4, we are using installed costs from \$.50 to \$2.00 per peak watt as spanning the range of costs generally anticipated by 1988. These costs, as used here, reflect only the PV panels, their mounting, and connecting copper cabling as described above. Power conditioning, storage, etc., are otherwise covered as discussed in a later section dealing with combining these modules into the overall system. The installed module cost then is \$200,000 to \$800,000 for the 400-kWp module excluding land costs.

## THE ELECTROLYZER MODULE

Today's electrolysis plants are predicated on power from an a-c grid which is rectified and then fed to the electrolyzers through an active power controller which feeds the units optimally. As a consequence, electrolyzer optimization has tended toward larger cell areas and lower voltage and higher current than those considered here (i.e., 200-V, 1,000-A units in series as opposed to 500-V, 800-A). For this study, it is assumed that a block purchase of 60- to 100-MW of electrolyzer will permit production-basis construction of units meeting the needs of the facility.

when consideration is given to using electrolyzers in conjunction with a PV array as the electricity source, the usual design approach encompasses d-c to d-c power conditioning systems to "track" the peak power point of the PV array while meeting the current/voltage polarization curve requirements of the electrolyzer and also adjusting to varying insolation levels throughout the day. Such conditioning systems can result in the loss of 5% to 10% of the power ahead of the electrolyzer.

Based on studies at E:R (Ref. 5) and elsewhere (e.g., Ref. 6), it is possible, however, to achieve good matching of the PV power source to the electrolyzer without the use of an active control system. This matching simply requires that the PV array and electrolyzer be specially designed so that the locus of the peak power points of the array, as insolation varies, approximates the voltage-current characteristics (polarization curve) of the electrolyzer.

An example of such a match for a 400-kWp module is shown in Figure 5. Also indicated in the figure are the boundaries in which the polarization curve must remain to keep mismatch losses below 5%. The PV-electrolyzer match will remain good over a wide range of operating conditions since thermal effects (i.e., operating temperatures) cause the locus of peak power points and the polarization curve to shift in the same general direction (to the left for higher temperatures; to the right for lower temperatures). The most severe mismatch likely to occur in a well-designed system will result from component aging and PV cell failures. As the electrolyzer ages, its polarization curve will shift to the right, while a deteriorating PV array will have the locus of peak power points shifted to the left in Figure 5. When, after several years, the mismatch becomes large, maintenance on both the array and the electrolyzer is mandated to restore efficient operation.

The direct coupling of an electrolyzer to a PV array is not a new idea (Refs. 7 and 8); however, directly coupled, well-matched systems have not yet been demonstrated. To this end, FSEC is currently implementing such a demonstration using a 2-kW electrolyzer specially built by Teledyne to E:R's specifications.

It is possible to design the electrolyzer so that at insolation levels above  $125\text{-W/m}^2$ , there is sufficient cell voltage for electrolysis to proceed. Below this level, the electrolyzer ceases functioning. In order to quantify potential losses due to periods of low insolation, solar data for calendar year 1981 (obtained from FSEC) has been examined. Of the annual tilted surface global insola-

tion measured, 97.8% was above the  $125\text{-W/m}^2$  threshold. In this analysis, the 15-minute data points as measured were combined into hourly values so that the 2.2% loss of available insolation probably represents an upper limit to the fraction of radiation which is unusable by a directly-connected electrolyzer of the type described.

It is expected that losses from the mismatch shown in Figure 5 will not exceed 2%. The additional loss of 2% unusable insolation results in a net 4% loss in matching. Note that this is better than that obtainable by using active power trackers and that this level should be achievable at an additional cost in contrast to the power-tracker situation.

Available electrolyzers in the 400-kW range are approximately 80% efficient (Ref. 9), i.e., it takes 1.25-kWhr of electricity to produce 1-kWhr of chemical energy in the hydrogen produced (higher heating value). These units, with no power conditioning, should cost approximately \$200/kW. The electrolyzers require double-deionized feedwater for satisfactory operation. Such a water conditioning plant for a 100-MW plant costs approximately \$100,000 (Ref. 10).

#### INTEGRATION OF 400-kWp PV MODULES

The full PV array ("super grid") size, using the stated 80% efficient electrolyzer and considering the usable average tilted surface global insolation measured by FSEC (1977-1982), turns out to be 67.5 MWp. Thus, 169 of the 400-kWp PV modules discussed previously are integrated into a "super grid" comprising the overall hydrogen-oxygen production system. The super grid is shown in Figure 6, and is 1.69 x 1.60 km in extent. This corresponds to 9.9 acres/MW, comparing favorably with the 9 acres/MW described for the SMUD array (Ref. 2). At \$.50 to \$2 per peak watt installed, such an array would cost \$33.8 to \$135.2 million not including the electrolyzers.

Three options for linking the array into a hydrogen-producing system are presented next. It will be recalled that these are: (1) a-c grid, (2) d-c grid, and (3) gaseous products grid (dispersed electrolyzers). For all the options investigated, the interconnections followed the routing shown in Figure 6, with a main trunk 1.69-km long with 26 branches of 0.8-km each. This provides optimal grid conditions for all three options considered.

Of the three options cited, the first two allow for the possible reclamation of the rejected low-temperature heat from a central electrolyzer facility. The heat is a direct result of electrolyzer inefficiency (20%) and amounts to about 250 million Btu/day at about 200°F. For perspective, this heat source is

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equivalent to a large flat-plate solar thermal array which is intrinsic to the central electrolyzer approach. In each case, central water purification is accomplished starting with municipal potable water. Water costs turn out to be negligible. For the dispersed electrolyzer configuration only, a pump with 50-gpm capacity to feed water to the dispersed electrolyzers is assumed in each at 50 psi head to compensate for pipe friction.

Each of the three grid configuration options is discussed next.

### (1) Distributed Inverters and an a-c Network

This design approach equates to that used when feeding a conventional utility a-c grid with power from the PV modules. An inverter-transformer is placed at the power-tie point of each 400-kWp PV module which then feeds a 35-kV a-c grid. At the central electrolyzer facility (on the north side of the overall array), the power is fed to a transformer-rectifier and power conditioning unit before being bused to the electrolyzers. Losses are taken as 5% in the inverters and 4% in the power conditioning for a 91% system throughput to the electrolyzer cells.

The principal advantage of this scheme is the use of existing technology and available components from inverter through product gas collection. Another advantage is that early-a.m. and late-p.m. low levels of insolation can be used to drive an appropriate subset of the electrolyzer units maintaining optimal current and voltage control.

Costs for the a-c lines were taken as \$10/foot installed, which, for the 13 miles of line, is approximately \$700,000. The inverters were taken as \$50/kW for a total of \$3.4 million. Power conditioning at the central electrolyzer plant at \$20/kW amounts to \$1.3 million. The electrolyzers themselves, at \$200/kW, amount to \$12.3 million and are housed in a \$200,000 building.

### (2) d-c Busbar Integration and Central Electrolysis

In this option, the 169 PV modules are tied by copper busbars carrying 500-V d-c power along the branches to the main trunk. Copper cabling costs were taken at \$4.1 installed.

The grid pattern shown in Figure 6 resulted in the use of 223.5 metric tons of copper being installed at a cost of \$2 million. Resulting ohmic losses in this design were 4.3-MW at peak insolation--6.4% of total power. At less than peak power conditions, the losses are less. The overall ohmic loss is estimated at 5% throughout the day. Doubling the amount of copper would result in roughly halving peak ohmic losses.

An alternative design with 13 d-c busbars running north and south and tied to a collector bus on the north edge of the full array was also considered. This resulted in 376.5 metric tons of copper installed at a cost of \$3.3 million and a peak ohmic loss of 3.64 MW.

A comparison of the two designs indicates a trade-off between \$1.3 million in copper and .65 MW of array (assumed to make up for the losses). At installed PV costs of less than \$2/W (peak), this represents a cost penalty; at \$2/W (peak), there is a breakeven situation.

Total costs for this option as used in the following analysis are \$12.8 million for electrolyzers housed in a \$200,000 building; \$2 million for the copper busbars installed into the grid pattern. Losses in the d-c busbar case are 5% in ohmic losses in the copper, and the 4% in threshold insolation and tracking mismatch mentioned in the electrolyzer discussion above, for a total system energy throughput efficiency of 91%.

### (3) Distributed Electrolyzer Network

In this option, a 400-kW electrolyzer matched to the 400-kWp PV array is installed at the power-tie point within each basic module and the hydrogen and oxygen produced are fed through a low-pressure gas distribution pipeline to a central collection point. Water is piped to each electrolyzer from a central purifier facility.

The water and product gas mains are laid in a common trench following the trunk and branch pattern of Figure 6. Pipe and main sizing and costs were calculated from Ref. 11 and were updated to 1982 dollars using a 7%/year inflation rate. Gas pressures were taken to be 70 psi at the electrolyzers and 10 psi at the central collection point. The water supply system to feed the water pipe is rated at 54.3 gpm.

Costs for this design are \$13.52 million for the electrolyzers and \$1 million for the three pipe grids (of properly varying diameter) as installed in the common trench. Losses in this design are only the 4% resulting from less than threshold insolation and non-optimized tracking between the PV array and the electrolyzer.

### CAPITAL COST COMPARISON OF THE THREE OPTIONS

Table 2 recaps the costs associated with constructing the three options considered for tying the system modules into an overall system which can provide hydrogen and oxygen to the liquefier facility. Elements of the overall system common to all three options (PV array, water conditioning, and gaseous

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storage) have been omitted in order to focus on interconnection costs alone. Using as a crude screening index the capital cost of the interconnect divided by yearly hydrogen capacity, we find that the most obvious candidate--distributed inverters--is the worst choice of the three options considered.

The central electrolyzer options, which allow electrolyzer-rejected heat recovery, have the potential of reducing hydrogen costs by \$.10/lb if 70% of the waste heat could be reclaimed at no capital cost. The comparison is based on fuel oil at \$8/10<sup>6</sup> Btu. Because of additional piping costs and, more significantly, heat loss in a hot water collection grid, the distributed electrolyzer option does not appear capable of heat reclamation. Note that the capital cost per yearly pound of hydrogen produced is a screening calculation only: The actual levelized cost over a 20-year period is derived in the last section of this paper. What can be deduced from the screening calculation presented herein is only the ranking of the three options.

Table 2. CAPITAL COSTS (in 10<sup>6</sup>\$) FOR THREE INTERCONNECTION OPTIONS

Options	(1)	(2)	(3)
Inverters	3.4	--	--
a-c Grid	.7	--	--
Power Cond.	1.3	--	--
d-c Bus	--	2.0	--
Gas/Water Mains	--	--	1.0
Electrolyzers	12.5	12.8	13.5
TOTAL	17.9	14.8	14.5
System Losses	9%	9%	4%
GH <sub>2</sub> Production (lbs/year)	5.46	5.46	5.76
Specific Capital Cost (\$/lb H <sub>2</sub> /year)	3.28	2.71	2.52

Based on these results, the distributed electrolyzer approach is tentatively seen to be the best choice, having 7.5% lower specific capital costs than the all-d-c/central electrolyzer option and 30% below the distributed inverter option. However, if electrolyzer rejected heat coproduct value is substantial, the choice might be the all-d-c/central electrolyzer option.

## REMAINDER OF THE SYSTEM

Liquid hydrogen is often the required form from the using system viewpoint (e.g., Space Shuttle). Also, large-scale delivery of hydrogen over distances of, say, 100 miles requires the liquid form (unless a gas pipeline is available). In order to render the hydro-

gen and oxygen into a truly usable form in such a large-scale facility, a liquefaction capability is included in the system.

To provide continuous operation of the liquefier, the system provides for one-day of gas storage. Two weeks of storage for the liquefied gases are also included. The liquefier chosen is an 8 ton/day hydrogen unit (5.84 X 10<sup>6</sup> lbs/year), with a corresponding liquefaction capacity for 63.5 tons/day oxygen. Capital costs for this plant are \$14.6 million and the electrical input required is 5.48 MW for 24 hours/day (Ref. 12).

To support such a plant wholly on renewable energy, 32-MWp of PV array is required (80 modules at 400-kWp each). This would be configured in the distributed inverter mode described earlier since the conventional liquefaction facility requires a-c power (d-c power might be used, but this option was not examined). This array size provides 8-hour operation of the plant directly, while charging 87.7-MWhr of battery storage to operate the liquefier during the other 16 hours of operation per day. It is important to operate the liquefier around-the-clock for both cost minimization and operating reasons, as next discussed.

Consideration was given to different size liquefiers and amounts of battery storage. Basically, this is a case of the trade-off between liquefier facility, photovoltaic array, and battery costs. At the extreme of no storage and operation on the PV array only, a 35 ton/day hydrogen unit would be required. Various intermediate sizes with some battery storage were also considered. The continuous operation of the liquefier plant selected was cheaper by \$8 to \$20 million than the no-storage alternative, and was essentially the same cost as the larger units which run at part capacity through the non-sun part of the day to reduce battery storage costs.

In the dedicated liquefier array, a 68.5-kW inverter capacity and 1.1-MWhr of battery storage are placed at each 400-kWp module. During the day when the PV module output exceeds 68.5 kW, the extra power is directed to storage. The placement of storage at the PV module allows the same inverter to be used for processing both the PV and battery outputs. The alternative is to use larger inverters and place battery storage at the liquefier plant--invoking rectification and increased inverter costs. This costs \$1.6 million more than the configuration presented here.

Costs for the liquefier subsystem then are \$14.6 million for the hydrogen and oxygen liquefier complex, \$16 to \$64 million for the dedicated PV array to power the liquefier, \$270,000 for inverters, \$330,000 for the a-c

grid, and \$8.77 million for the batteries (at \$100/kWhr). One day's gas storage for two gases is estimated at \$4.6 million using in-production LPG-type containers. Two weeks' storage for liquid oxygen costs \$400,000; for liquid hydrogen, the cost is \$1.6 million. Conventional spherical, vacuum-jacketed, field-constructed vessels of 217,000 and 400,000 gallons, respectively, are needed.

Figure 7 shows the overall facility physical layout as dominated by the two PV arrays. It is 1.65 square miles in area.

#### SUMMARY OF CAPITAL AND OPERATING & MAINTENANCE COST ESTIMATES

The combined costs for the entire system, including final liquid storage, are presented in Table 3. The range of costs shown represents the effects of considering installed PV module costs of from \$.50 to \$2 per peak watt.

Table 3. COST SUMMARY (MILLIONS OF DOLLARS)

	Capital	O&M
PV for Electrolyzer	33.8-135.2	--
PV for Liquefier	16 - 64	--
TOTAL PV	49.8-199.2	1.8-3.4
Liquefier	14.6	.75
Gas Storage	4.6	.46
Liquid Storage	2.0	.20
Interconnections		
& Electrolyzer	14.5	.29
Inverters, Grid		
& Batteries	9.4	.56
TOTALS	94.9-244.3	4.06-5.66 (4.3%-2.3%)

Operating and maintenance (O&M) costs were taken from Ref. 12 for the liquefier. The storage facility O&M costs were taken as 1% of purchase costs per year. The electrolyzer O&M cost was taken as 2%. The O&M costs for the power supply for the liquefier plant include the replacement of 5% of the batteries per year over the life of the system.

For the PV array, it is assumed that 3 kW of array is replaced each day to account for field failures. A crew of 50 individuals working a one-shift, 5-day week is included to perform inspections, do maintenance, and adjust the tilt of the arrays 10 times per year.

In review, photovoltaic array installed costs are dominant, being 53% to 82% of the required investment at \$.50/Wp and \$2/Wp, respectively. O&M costs related to the PV arrays are also prominent at 44% and 60%, respectively. The electrolyzer and the hydrogen/oxygen liquefier represent equal capital

costs at 15% and 6% of the total, respectively, for the two PV installed costs.

One-day product gas storage costs more than double 2-weeks' of liquid storage, but together are less than half the liquefier or electrolyzer costs. Actually, combined storage costs are only about two-thirds that of the sum of the inverter, electric or gas grid, and battery costs.

#### FINAL PRODUCT LEVELIZED COST

These capital costs and O&M expenses were evaluated by means of the Electric Power Research Institute's (EPRI) TAG model (Ref. 13) assuming 6% inflation and a 12% discount rate. Income taxes were taken as 48%; and property taxes and insurance at 2%. A 10% investment tax credit was taken and all equipment was depreciated over 10 years with a 20-year facility book life.

Under these assumptions, the levelized product cost for one pound of liquid hydrogen and the stoichiometrically-equivalent of liquid oxygen (8 lbs) is presented in Table 4.

In order to arrive at a liquid hydrogen cost alone, the cost of the oxygen must be subtracted from the above numbers. Using today's values (Ref. 12), with a 6% inflation rate, and a 3% escalation over inflation rate to reflect increasing electrical costs, the 20-year levelized cost of liquid oxygen corresponding to one pound of hydrogen is \$.60, i.e., \$.075/lb of liquid oxygen. Liquid hydrogen costs per pound, then, are \$7.38, \$4.05, and \$3.01 for installed photovoltaic array costs of \$2, \$1, and \$.50, respectively, per peak watt.

Table 4. LEVELIZED HYDROGEN AND OXYGEN COSTS

PV Installed Costs (\$/Wp)	Product Costs (\$)	
	1 lb LH <sub>2</sub> + 8 lb LO <sub>2</sub>	1 lb LH <sub>2</sub>
.50	3.61	3.01
1.00	4.65	4.05
2.00	7.98	7.38

#### DISCUSSION

Current delivered KSC costs are about \$2.72 lb for liquid hydrogen (Ref. 14) and about \$.045/lb for liquid oxygen (Ref. 15). As noted earlier, the hydrogen plant operating costs are tied to the price of natural gas, while oxygen plant operating costs are tied to electricity prices (to operate large air compressors mainly).

By initial comparison, the non-fossil product costs presented here (Table 4) appear non-competitive. However, recall that these



are levelized costs for a 20-year period, beginning no earlier than 1987. If conventionally-produced hydrogen and oxygen are compared on the same basis, with appropriate escalation-above-inflation of natural gas (or any fossil feedstock) and electricity, the non-fossil production falls into the competitive range. Using the same 6% inflation and 3% escalation rates as were used earlier for liquid oxygen, the 20-year levelized cost for liquid hydrogen becomes \$5.63/lb--within the range of the costs presented for PV. If the photovoltaic installed costs were to be about \$1.50/Wp, cost parity between conventionally-produced and the subject facility-produced liquid hydrogen could be achievable.

By 1990, installed PV arrays without power conditioning costing \$2/Wp seem likely (Ref. 4). It is possible that, using such technologies as amorphous thin-film cells and innovative balance-of-system design, costs could be even lower, although the \$.50/Wp number used as the low end of the cost range in this paper may not, in fact, be attainable.

One possible means of reducing costs would be consideration of fully-tracking PV arrays, which would produce approximately 20% more energy per year than the essentially fixed, manually tilted arrays considered here. O&M costs would be correspondingly reduced. The tracking would not have to be anywhere near as precise as that for a power tower, for which operating examples exist. Several PV projects have been recently announced which provide this full-tracking capability. However, it should be noted that as installed PV panel costs are brought down, the system cost-fraction required for full-tracking goes up proportionately.

We have not addressed the automatic monitoring of the performance of the 400-kWp modules, or the submodules which constitute the module. It is possible that the use of microcomputer chips with A-D converters could be installed to provide the monitoring, but associated costs have not been estimated and the size of the smallest element to be monitored has not been determined. This may be another avenue for decreasing O&M costs.

As should be clearly evident in the foregoing presentation, the facility described is entirely stand-alone, requiring only solar energy and water and no other input energy, e.g., utility power, fuel. Alternatively, there appears to be a number of powerful incentives for introducing electric utility grid interfacing to the benefit of resulting product costs. For example, operating the liquefier on utility power during non-sun periods would reduce the associated PV array size and costs, and eliminate the need for batteries. From the utility point of view, this might equate generally to an off-peak,

night-time load, providing for favorable rates.

Going the other way, mid-day PV power might be supplied in some fractional part to the utility during peak-load periods at favorable purchase rates by the utility. Electrolyzer input could be correspondingly reduced at those times which would act to raise the efficiency of the electrolysis process. It may even be the case that the utility might take some of the hydrogen and oxygen products for its own use at a price (e.g., for peaking power). Such prospective facility "cooperative grid interaction," though of high interest and to be initially explored in the present KSC study contract, remains beyond the scope of this paper.

#### CONCLUDING REMARKS

As an exemplary non-fossil liquid hydrogen/liquid oxygen production approach, the 1.65 square mile, 100-MWp facility laid out (but not optimized) here could provide competitively-priced product for the 2-decade period beginning around 1987-1992. Product costs remain highly sensitive to installed photovoltaic costs assumed since these dominate the total facility capital costs (the range of 50% to 85%).

Further study of the PV approach should be made, in perspective with alternative non-fossil hydrogen production approaches, to deepen this inquiry (sensitivity studies, innovative designs, etc.). Such variants as full-tracking arrays and electric utility interfacing should be included. Realistic projections for conventional (and unconventional) fossil-based production costs for the same period should obviously be developed as a basis for comparison and future decision-making.

It would appear from this and other contemporary assessments, that energy planners within NASA and elsewhere can begin to look seriously at this one avenue and others supportive of the long-term transition to a sustainable, non-fossil energy system.

#### ACKNOWLEDGMENTS

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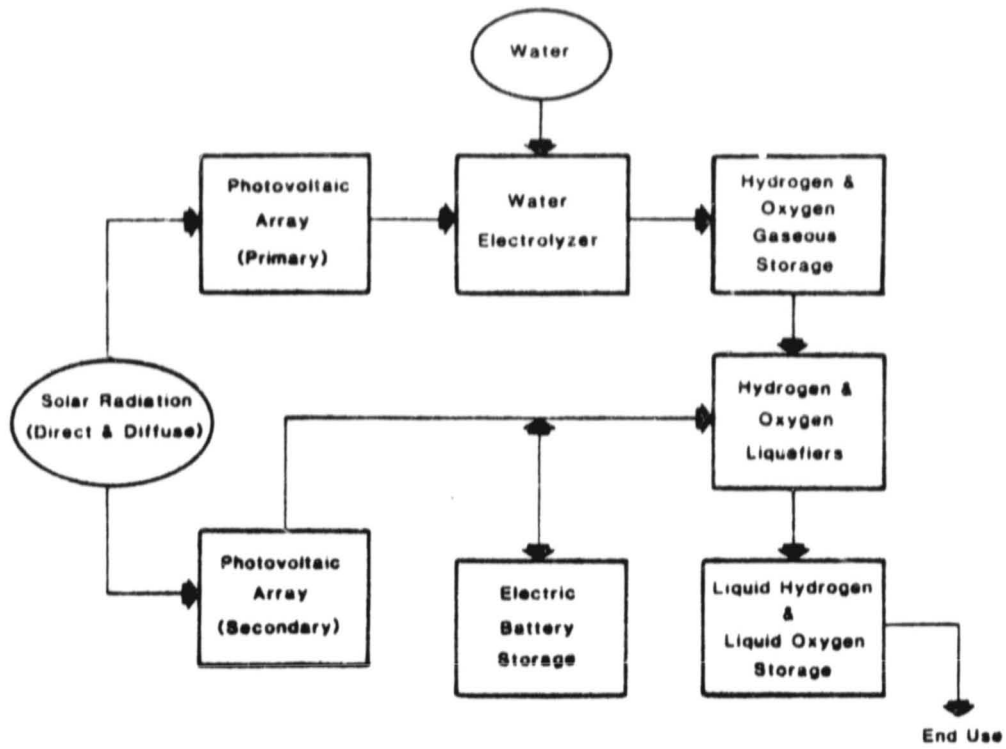


Figure 1. OVERALL SYSTEM FUNCTIONAL DIAGRAM

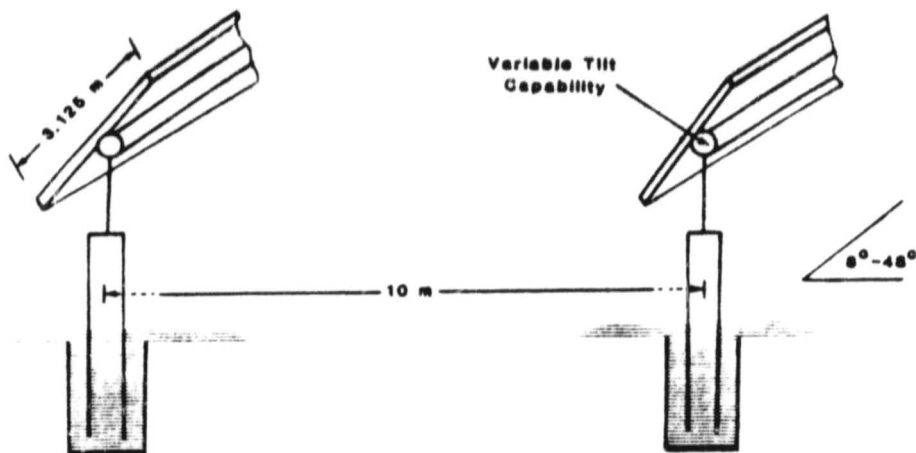


Figure 2. GEOMETRY OF TILTABLE, SOUTH-FACING PHOTOVOLTAIC PANELS (TYPICAL)

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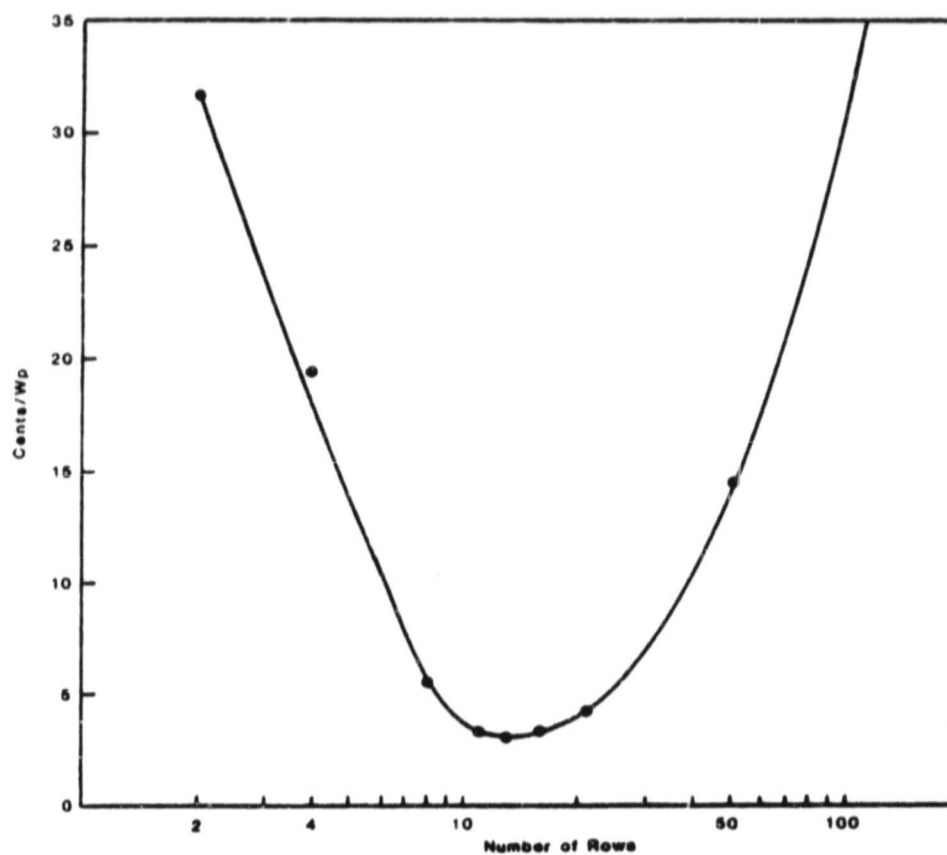


Figure 3. COPPER COSTS FOR 400-kwp ARRAY MODULE AS A FUNCTION OF  
NUMBER OF ROWS

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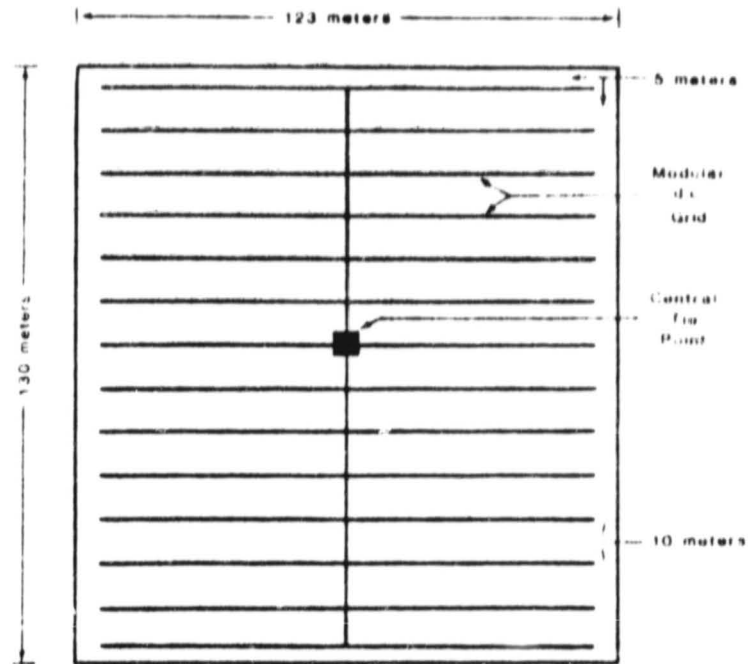


FIGURE 4. THE 100-KWP PV ARRAY MODULE

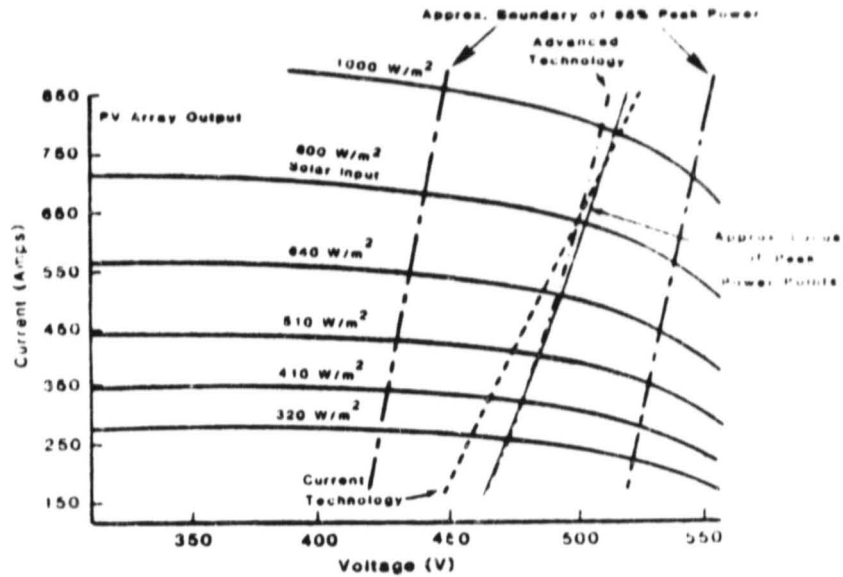


FIGURE 5. OPERATING REGION OF A CENTRAL FIN  
CONNECTED, PHOTOVOLTAIC WATER HEATING

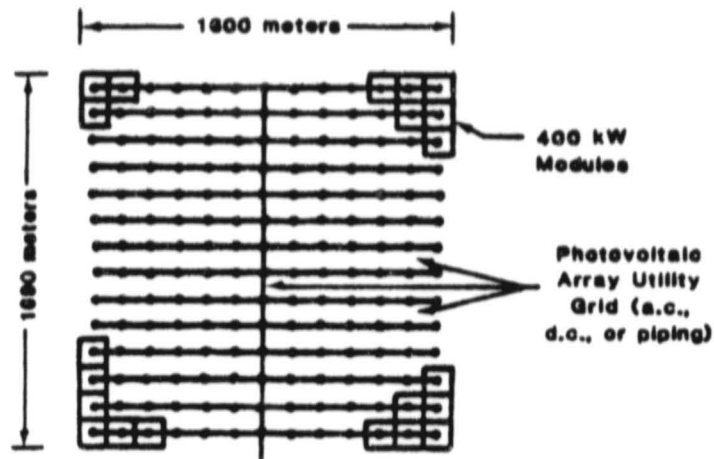


Figure 6. OVERALL PRIMARY PHOTOVOLTAIC SYSTEM ARRAY AND INTERCONNECTION GRID

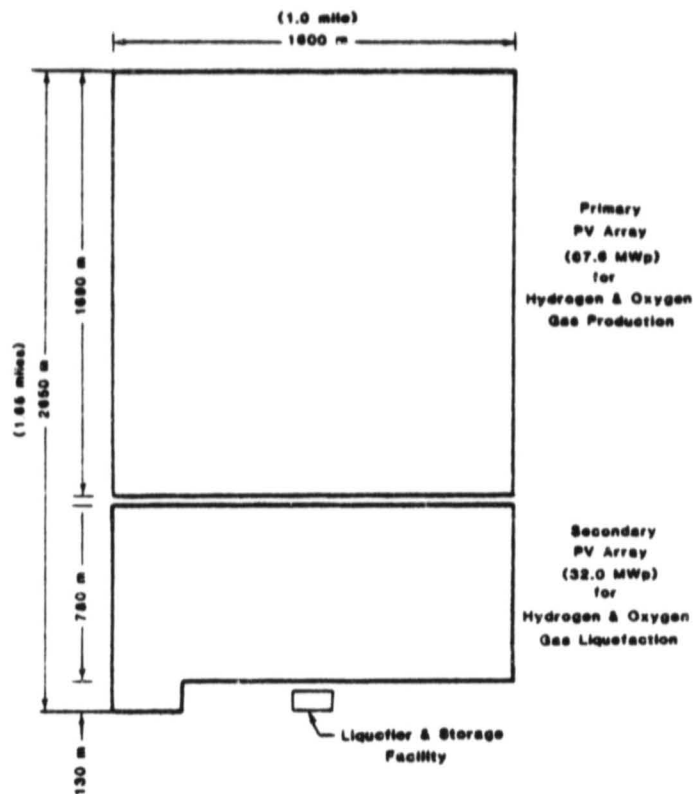


Figure 7. OVERALL PHYSICAL LAYOUT OF FACILITY